Mission

The mission of Columbia Engineering (The Fu Foundation School of Engineering and Applied Science) is to expand knowledge and advance technology through research, while educating students to become leaders and innovators informed by an engineering foundation. Enriched with the intellectual resources of a global university in the City of New York, we push disciplinary frontiers, confront complex issues, and engineer innovative solutions to address the grand challenges of our time. We create a collaborative environment that embraces interdisciplinary thought, creativity, integrated entrepreneurship, cultural awareness, and social responsibility, and advances the translation of ideas into innovations that impact humanity.

Our mission can be encapsulated as “Transcending Disciplines, Educating Leaders, Transforming Lives.”
Welcome to Columbia Engineering! You are embarking on a new year of study in some of the most exciting areas of inquiry of our time. Each year, Columbia engineers pursue a robust course of study of great depth and breadth, one that prepares them for a variety of pursuits in engineering and applied science, as well as many other fields and industries.

Our community has a long history of scientific and engineering breakthroughs that have impacted our world. From the School's beginning in 1864 through today, the work of faculty, alumni, and students has pushed disciplinary frontiers to create, invent, and innovate devices, materials, tools, and processes to make life better.

Our first dean, Charles Frederick Chandler, served as president of New York City's Metropolitan Board of Health. In this role, he crusaded to ensure the purity of food and drugs, the safety of milk, the availability of clean water in the city, and the introduction of building codes.

Over the years, we have continued to serve the community around us, as well as the nation and the world, with research that makes a direct impact on the present and paves the way for a more sustainable, healthy, secure, connected, creative, and equitable future.

At Columbia Engineering, faculty and students work closely together to confront the most interesting and pressing challenges of our time. From climate change and urbanization to women's health and emergency response, we are working together to find solutions, bolstered by state-of-the-art facilities and labs and the world-leading schools, centers, and initiatives that comprise Columbia University.

There has never been a better time to be a Columbia engineer. I encourage you to seek out the exceptional opportunities for learning and advancement that await you here.

With best wishes for the academic year,

Shih-Fu Chang
Dean, Columbia Engineering
Richard Dicker Professor of Electrical Engineering and Computer Science
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About the School and University
A COLONIAL CHARTER
Since its founding in 1754, as King’s College, Columbia University has always been an institution both of and for the City of New York. And it has always been an institution of and for engineers. In its original charter, the College stated that it would teach, among other things, “the arts of Number and Measuring, of Surveying and Navigation, . . . the knowledge of . . . Meteors, Stones, Mines and Minerals, Plants and Animals, and everything useful for the Comfort, the Convenience and Elegance of Life.”

A MODERN SCHOOL FOR MODERN TIMES
The School of Mines became the School of Mines, Engineering, and Chemistry in 1896, and its professors included Michael Idvorsky Pupin, a graduate of the Columbia College Class of 1883. As a professor at Columbia, Pupin did pioneering work in carrier-wave detection and current analysis, with important applications in radio broadcasting. He is perhaps most famous for having invented the “Pupin coil,” which extended the range of long-distance telephones.

An early student of Pupin’s was Irving Langmuir. Langmuir, Class of 1903, enjoyed a long career at the General Electric research laboratory. There he invented a gas-filled tungsten lamp, contributed to the development of the radio vacuum tube, and extended Gilbert Lewis’s work on electron bonding and atomic structure. His research in monolayering and surface chemistry led to a Nobel Prize in Chemistry in 1932.

But early work on radio vacuum tubes was not restricted to private industry. Working with Pupin, an engineering student named Edwin Howard Armstrong was conducting experiments with the Audion tube in the basement of Philosophy Hall when he discovered how to amplify radio signals through regenerative circuits. Armstrong, Class of 1913, was stationed in France during the First World War, where he invented the superheterodyne circuit to tune in and detect the frequencies of enemy aircraft ignition systems. After the war, Armstrong improved his method of frequency modulation (FM), and by 1931, had both eliminated the static and improved the fidelity of radio broadcasting forever. The historic significance of Armstrong’s contributions was recognized by the U.S. government when the Philosophy Hall laboratory was designated a National Historic Landmark in 2003.

As the United States evolved into a major twentieth-century political power, the University continued to build onto its undergraduate curriculum the broad range of influential graduate and professional schools that define it today. Renamed once again in 1926, the School of Engineering prepared students for careers not only as engineers of nuclear-age technology, but as leaders engaged with the far-reaching political implications of that technology as well.

After receiving a master’s degree from the School in 1929, Admiral Hyman George Rickover served during the Second World War as head of the electrical section of the Navy’s Bureau of Ships. A proponent of nuclear sea power, Rickover directed the planning and construction of the world’s first nuclear submarine, the 300-foot-long Nautilus, launched in 1954.

TECHNOLOGY AND BEYOND
Today, The Fu Foundation School of Engineering and Applied Science, as it was named in 1997, continues to
provide leadership for scientific and educational advances. Even Joseph Engelberger, Class of 1946, the father of modern robotics, could not have anticipated the revolutionary speed with which cumbersome and expensive “big science” computers would shrink to the size of a wallet.

No one could have imagined the explosive growth of technology and its interdisciplinary impact. Columbia Engineering is in a unique position to take advantage of the research facilities and talents housed at Columbia to form relationships among and between other schools and departments within the University. Biomedical Engineering, with close ties to the Medical School, is but one example. Interdisciplinary centers are the norm, with cross-disciplinary research going on in biomedical imaging, environmental chemistry, materials science, nanotechnology, digital, and new media technologies. The School and its departments have links to the Departments of Physics, Chemistry, Earth Science, and Mathematics, as well as the College of Physicians and Surgeons, the Graduate School of Journalism, Lamont-Doherty Earth Observatory, The Earth Institute, Teachers College, Columbia Business School, and the Graduate School of Architecture, Planning and Preservation. The transforming gift of The Fu Foundation has catapulted the School into the forefront of collaborative research and teaching and has given students the opportunity to work with prize-winning academicians, including Nobel laureates from many disciplines.

NEW RESEARCH FRONTIERS
Columbia’s technology transfer office, Columbia Technology Ventures, works with faculty inventors to commercialize ideas and brings in millions in licensing revenue annually. Columbia Engineering faculty have been instrumental in developing some of the most successful inventions in consumer electronics, as well as establishing many of the widely accepted global standards for storage and transmission of high-quality audio and video data. Columbia is the only university actively participating in a broad range of standards-based patent pools, including AVC (Advanced Video Coding), the world standard for audio/video compression that is now one of the most commonly used HD formats and most commonly employed in streaming media; and ATSC, a standard developed by the Advanced Television Systems Committee for digital television transmission. It is now the U.S. standard for recording and retrieval of data and HD audio-visual media. In addition to the standards, Columbia Engineering faculty have patents in areas as diverse as modular cameras, carbon capture, a search engine that matches facial features, and even methods to combat virtual reality sickness.

Increasingly, the inventions emerging from Columbia Engineering are developed in collaboration with other researchers, expanding the potential applications for their important work. Programs such as the Columbia Biomedical Technology Accelerator (BiomedX), PowerBridgeNY, the NYC Media Lab Combine program,
the COSMOS Wireless Testbed, the Columbia IBM-Center for Blockchain and Data Transparency, and the Columbia Electrochemical Energy Center are strengthening interdisciplinary capacity and fostering an entrepreneurial and inventive energy within the School. Some of these programs and centers have helped prepare ideas for commercialization, including personalized robotics for use in physical rehabilitation and an implantable device that acts as a minimally-invasive glucose sensor for diabetic patients.

**ENTREPRENEURSHIP**

Throughout the academic year, the School hosts many activities and networking events to support its active startup community, including the Columbia Engineering Fast Pitch Competition, Columbia Venture Competition, Design Challenges, Hackathons, and the Ignition Grants program, which funds ventures started by current students.

An exciting way the School fosters entrepreneurship is with its BiomedX Program. A major goal of the program is to educate researchers, clinicians, and students about the many aspects involved in commercializing biomedical innovation.

Entrepreneurship remains an important central educational theme at Columbia Engineering. The School offers a range of programs and a 15-credit, interdisciplinary minor in entrepreneurship made up of both Engineering and Business School courses. The School also provides a four-year entrepreneurship experience for all interested Columbia Engineering students, regardless of major.

And for alumni, entrepreneurial support continues. The Columbia Startup Lab, a coworking facility located in SoHo, provides subsidized space for Columbia alumni entrepreneurs to house and nurture their fledgling ventures. The Lab is the result of a unique partnership between the deans of Columbia College and the Schools of Business, Engineering, Law, and International and Public Affairs.

**A FORWARD-LOOKING TRADITION**

But, for all its change, there is still a continuous educational thread that remains the same. Committed to the educational philosophy that a broad, rigorous exposure to the liberal arts provides the surest chart with which an engineer can navigate the future, all undergraduates must complete a modified but equally rigorous version of Columbia College’s celebrated Core Curriculum. It is these selected courses in contemporary civilization in the West and other global cultures that best prepare a student for advanced coursework; a wide range of eventual professions; and a continuing, life-long pursuit of knowledge, understanding, and social perspective. It is also these Core courses that most closely tie today’s student to the alumni of centuries past. Through a shared exposure to the nontechnical areas, all Columbia Engineering students—past, present, and future—gain the humanistic tools needed to build lives not solely as technical innovators, but as social and political ones as well.

**A COLLEGE WITHIN THE UNIVERSITY**

Combining the advantages of a small college with the extensive resources of a major research university, students at Columbia Engineering pursue their academic interests under the guidance of outstanding senior faculty members who teach both undergraduate and graduate-level courses. Encouraged by the faculty to undertake research at all levels, students at the School receive the kind of personal attention that only Columbia’s exceptionally high faculty-student ratio affords.

**THE NEW YORK ADVANTAGE**

Besides the faculty, the single greatest resource for students is without doubt the City of New York. Within easy reach by walking, bus, subway, or taxi, New York’s broad range of social, cultural, and business communities offer an unparallelled opportunity for students to expand their horizons or deepen their understanding of almost any human endeavor imaginable. With art from small Chelsea galleries to major museums; music from Harlem jazz clubs to the Metropolitan Opera; theater from performance art in the East Village to musicals on Broadway; food from around the world; and every sport imaginable, New York is the cultural crossroads of the world.

New York is also a major player in high-tech research and development, where Fortune 500 companies traded on Wall Street seek partnerships with high-tech startups in Tribeca and Brooklyn. As part of the research community themselves, Columbia students have exceptional opportunities for contact with industry both on and off campus. Senior representatives of these companies often visit Columbia to lecture as adjunct faculty members or as guest speakers, and undergraduate and graduate students frequently undertake research or internships with these and other companies, oftentimes leading to offers of full-time employment after graduation.

In addition to its ties to private industry, Columbia also has a historically close relationship with the public sector of New York, stretching back to the eighteenth century. No other city in the world offers as many impressive examples of the built environment—the world’s most famous collection of skyscrapers, long-span bridges, road and railroad tunnels, and one of the world’s largest subway and water supply systems. Involved in all aspects of the city’s growth and capital improvements over the years, Columbia engineers have been responsible for the design, analysis, and maintenance of New York’s enormous infrastructure of municipal services and communications links, as well as its great buildings, bridges, tunnels, and monuments.

**THE UNIVERSITY AT LARGE**

Columbia University occupies three major campuses, as well as additional special-purpose facilities throughout the area. The main campus is located on the Upper West Side in Morningside Heights, and the Manhattanville campus is the newest addition to Columbia University. This open and
environmentally sustainable campus will grow over the next decade to encompass more than 17 acres. Further uptown in Washington Heights is the Columbia University Irving Medical Center (CUIMC), which includes Columbia’s College of Physicians and Surgeons, the Mailman School of Public Health, the New York State Psychiatric Institute, College of Dental Medicine, and School of Nursing. CUIMC is the world’s first academic medical center, and opened in 1928 when Columbia’s health-related schools and Presbyterian Hospital (now New York-Presbyterian Hospital) moved to the Washington Heights location. Columbia Engineering’s Biomedical Engineering Department has offices on both the Morningside campus and CUIMC.

Beyond its schools and programs, the measure of Columbia’s true breadth and depth must take into account its internationally recognized centers and institutions for specialized research. These centers study everything from human rights to molecular recognition and hold close affiliations with Teachers College, Barnard College, the Juilliard School, and both the Jewish and Union Theological Seminaries. Columbia also maintains major off-campus facilities such as the Lamont-Doherty Earth Observatory in Palisades, NY, and the Nevis Laboratories in Irvington, NY. Involved in many cooperative ventures, Columbia also conducts ongoing research at such facilities as Brookhaven National Laboratory in Upton, NY, and the NASA Goddard Institute for Space Studies located just off the Morningside campus.

THE MORNINGSIDE HEIGHTS CAMPUS

Columbia Engineering is located on Columbia’s Morningside campus. One of the handsomest urban institutions in the country, the 131 million gross square feet (gsf) of the Morningside campus comprise more than 200 buildings of housing; off-campus apartments and commercial buildings; recreation and research facilities; centers for the humanities and social and pure sciences; and professional schools in architecture, business, the fine arts, journalism, law, and many other fields.

MANHATTANVILLE CAMPUS

From Broadway and 125th Street West to a revitalized Hudson River waterfront, Columbia’s 17-acre Manhattanville campus is a welcoming environment of publicly accessible open space, tree-lined streets, neighborhood-friendly retail, and innovative academic buildings that invite community engagement. It is home to the Jerome L. Greene Science Center, Columbia’s Mortimer B. Zuckerman Mind Brain Behavior Institute, the Lenfest Center for the Arts, and the University Forum, an event and meeting space. Columbia Business School has relocated to this campus, and plans are underway to develop a new building here for Columbia Engineering, as well. These spaces house cutting-edge research and teaching in brain science, an art gallery, screening room, and performance spaces, and space for active community engagement.

COLUMBIA ENGINEERING

Columbia Engineering occupies four laboratory and classroom buildings at the north end of the Morningside campus, including the Northwest Corner Science and Engineering Building, an interdisciplinary teaching and research building. In this building researchers from across the University work together to create new areas of knowledge, in fields where the biological, physical, and digital worlds fuse. This puckish frontier will advance some of modern society’s most challenging problems in a wide range of sectors, from health to cybersecurity, from smart infrastructure to the environment.

Supporting multiple programs of study, the School’s facilities are designed and equipped to meet the laboratory and research needs of both undergraduate and graduate students. The School is also the site of an almost overwhelming array of basic and advanced research installations, such as the Columbia Genome Center and the Columbia Nano Initiative, established to serve as the hub for multidisciplinary and collaborative research programs in nanoscale science and engineering. Shared facilities and equipment to support nano research at the Engineering School include a state-of-the-art clean room in the Schapiro Center for Engineering and Physical Science Research (CEPSR) and a Transmission Electron Microscope (TEM) Laboratory on the first floor of Havemeyer.

Founded in 2012 by Columbia Engineering, the Data Science Institute also sits on the Morningside campus as a University-wide resource that spans nine schools, including Journalism, the Graduate School of Arts and Sciences, and the Columbia University Irving Medical Center. The mission of the Data Science Institute is to train data science innovators and develop ideas for the social good.

Details about specific programs’ laboratories and equipment can be found in the sections describing those programs.

Columbia Engineering Computing Facilities

The Botwinick Multimedia Learning Laboratory at Columbia University has redefined the way engineers are educated here.

Designed with both education and interaction in mind, the lab provides students and instructors with:

- 48 desktops
- A full set of professional-grade engineering software tools
- A collaborative classroom learning environment

The lab is utilized in some of the School’s introductory first-year engineering projects, as well as advanced classes in modeling and animation, technology and society, and entrepreneurship.

The Makerspace

Columbia Engineering’s Makerspace provides students with a dedicated place to collaborate, learn, explore, experiment, and create prototypes. Students can utilize the space to work...
on a variety of innovative projects, including independent or group design projects, product development, and new venture plans. This facility fosters student creativity by bringing together the workspace and tools for 3D printing, laser cutting, computer-aided design, physical prototyping, fabric arts, wood- and metalworking, jewelry making, sewing and embroidery, stained glass making, electronics, and software.

**Carleton Commons**
Located on the fourth floor (campus level) of the Mudd Building, Carleton Commons and Blue Java Café comprise 3,200 square feet with seating for 160 and areas for casual meetings, individual and group work, and quiet study. Carleton Commons gives students a dedicated and comfortable space to gather, relax between classes, or meet and work with one another on problem sets or projects. The new design also enables flexible and reconfigurable use of the space for larger gatherings and special events.
Undergraduate Studies
The undergraduate programs at Columbia Engineering not only are academically exciting and technically innovative but also lead into a wide range of career paths for the educated citizen of the twenty-first century. Whether you want to become a professional engineer, work in industry or government, or plan to pursue a career in the physical and social sciences, medicine, law, business, or education, Columbia Engineering will provide you with an unparalleled education.

The School firmly believes that students gain the most when engineering is brought up front, early in the four-year curriculum. Therefore, each first-year student takes the Art of Engineering, which addresses the fundamental concepts of math and science in an engineering context, as well as nontechnical issues in professional engineering practice such as ethics and project management.

In addition to in-depth exploration of engineering and applied science, Columbia Engineering undergraduates explore the humanities and social sciences with Columbia College students through intellectually challenging Core Curriculum courses taught by the Faculty of Arts and Sciences. These courses in art, literature, music, major cultures, and economics, among others, provide students with a broad, intellectually disciplined, cultural perspective on the times they live in and the work they do.

James H. and Christine Turk Berick Center for Student Advising
403 Lerner Hall, MC 1201
212-854-6378
csa@columbia.edu
cc-seas.columbia.edu/csa

The James H. and Christine Turk Berick Center for Student Advising (CSA) guides and supports undergraduates at Columbia College and Columbia Engineering as they navigate their educations and lives at Columbia University. Individually and collaboratively, each advising dean:

- provides individual and group academic advisement and counseling
- provides information on preprofessional studies, major declaration, and completion of the degree, as well as various leadership, career, graduate school, and research opportunities
- interprets and disseminates information regarding University policies, procedures, resources, and programs
- educates and empowers students to take responsibility in making informed decisions
- refers students to additional campus resources

Every undergraduate is assigned an adviser from the Berick Center for Student Advising for the duration of their undergraduate career. Generally, each matriculating student is assigned to an advising dean who is a liaison to the department the student indicated as their first intended major on the Columbia application. When a student declares a major, a faculty member is also appointed to advise them for the next two years. Depending on their chosen major, students may be assigned to a new advising dean who is a CSA liaison to their department. Advising deans regularly refer students to their academic departments to receive expert advice about their engineering course selections.

Preprofessional Advising
Preprofessional Advising is a specialized advising unit within the James H. and Christine Turk Berick Center for Student Advising. It is dedicated to providing information
and guidance to students who plan a career in law or the health professions, through individual advising, workshops, and other events related to professions of law and health. Preprofessional advisers work closely with other CSA advisers to support students during their undergraduate program of study. They also provide extensive individualized support to students and alumni through their application process to professional schools.

POLICY ON DEGREE REQUIREMENTS
The Committee on Instruction and faculty of The Fu Foundation School of Engineering and Applied Science review degree requirements and curricula matters each year, and the bulletin reflects these faculty recommendations and curricular changes in its yearly reprinting. School policy requires students to fulfill all general degree requirements as stated in the bulletin of the first year of their matriculation into the School. Students declare their major during the first semester of their sophomore year. Requirements for the major or minor are in accordance with the bulletin during the year in which the student declares the major or minor.

THE FIRST-YEAR/SOPHOMORE PROGRAM
Students entering Columbia Engineering are encouraged to consider the wide range of possibilities open to them, both academically and professionally. To this end, the first and second years of the four-year undergraduate program comprise approximately half the total number of credits required for the degree that expose students to a cross-fertilization of ideas from different disciplines within the University. The sequence of study proceeds from an engagement with engineering and scientific fundamentals, along with humanities and social sciences, toward an increasingly focused training in the third and fourth years designed to give students mastery of certain principles and arts central to engineering and applied science.

Liberal Arts Core for Columbia Engineering Students: 27-Point Nontechnical Requirement
This requirement provides a broad liberal arts component that enhances the Engineering professional curriculum to help students meet the challenges of the twenty-first century. Our students are destined to be leaders in their professions and will require sophisticated communication, planning, and management skills. The Committee on Instruction established the School’s nontechnical requirement so that students would learn perspectives and principles of the humanities and social sciences as part of a well-rounded and multiperspective education. Through discussion, debate, and writing, students improve their abilities to engage in ethical, analytic, discursive, and imaginative thinking that will prove indispensable later in life.

- Engineering students must take 16 to 18 points of credit of required courses in list A and 9 to 11 elective points chosen from the approved courses in list B. The total combined number of nontechnical points (from lists A and B, below) must add up to at least 27. Neither list can be modified by advising deans or faculty advisers.
- Advanced Placement (AP) credit in appropriate subject areas can be applied toward the 9-point elective nontechnical requirement and for Principles of Economics.

A. Required Nontechnical Courses
(16–18 points of credit)
These courses must be taken at Columbia.
1. ENGL CC1010: University writing (3 points)
2. One of the following two-semester sequences: HUMA CC1001-CC1002: Masterpieces of Western literature and philosophy (All students registering for this course should be prepared to discuss books 1–12 of the Iliad on the first day of class) or COCI CC1101-CC1102: Introduction to contemporary civilization in the West or Global Core: Any two courses from approved list (6–8 points) If electing Global Core, students must take two courses from the List of Approved Courses (bulletin.columbia.edu/columbia-college/core-curriculum/global-core-requirement/) for a letter grade.
3. One of the following two courses: HUMA UN1121: Masterpieces of Western art, or HUMA UN1123: Masterpieces of Western music (3 points)
4. ECON UN1105: Principles of economics. (This course can be satisfied through Advanced Placement; see the Advanced Placement chart on page 12.) Note: Engineering students may not take any Barnard class as a substitute for ECON UN1105, (4 points)

B. Elective Nontechnical Courses
(9–11 points of credit)
The following course listing by department specifies the Columbia College, Barnard, or Columbia Engineering courses that either fulfill or do not fulfill the nontechnical requirement.
(Professional, workshop, lab, project, scientific, studio, music instruction, and master’s-level professional courses do not satisfy the 27-point nontechnical requirement.)

AFRICAN-AMERICAN STUDIES: All courses
AMERICAN STUDIES: All courses
ANCIENT STUDIES: All courses
ANTHROPOLOGY: All courses in socio-cultural anthropology
All courses in archaeology except fieldwork
No courses in biological/physical anthropology [UN1010, UN1011, UN3204, UN3940, GU4147-GU4148, GU4200, GU4700]
ARCHITECTURE: No courses
ART HISTORY AND ARCHEOLOGY: All courses
ASIAN AMERICAN STUDIES: All courses
ASTRONOMY: No courses
BIOLOGICAL SCIENCES: No courses
BUSINESS: No courses
CHEMISTRY: No courses
CLASSICS: All courses
COLLOQUIA: All courses
COMPARATIVE ETHNIC STUDIES: All courses
COMPARATIVE LITERATURE AND SOCIETY: All courses

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COMPUTER SCIENCE: No courses

CREATIVE WRITING: All courses (This is an exception to the workshop rule.)

DANCE: All courses except performance classes

DRAMA AND THEATRE ARTS: All courses except workshops, rehearsal, or performance classes

EARTH AND ENVIRONMENTAL SCIENCES: No courses

EAST ASIAN LANGUAGES AND CULTURE: All courses

ECOLOGY, EVOLUTION, AND ENVIRONMENTAL BIOLOGY: No courses except EEEB GU4321 or GU4700

ECONOMICS: All courses except UN3025 Financial economics
UN3211 Intermediate microeconomics
UN3213 Intermediate macroeconomics
UN3412 Introduction to econometrics
UN3981 Applied econometrics
GU4020 Economics of uncertainty and information
GU4211 Advanced microeconomics
GU4213 Advanced macroeconomics
GU4251 Industrial organization
GU4260 Marketing design
GU4280 Corporate finance
GU4301 Economic growth and development
GU4412 Advanced econometrics
GU4413 Econometrics of time series and forecasting
GU4415 Game theory
GU4505 International macroeconomics
GU4526 Transition reforms, globalization, and financial crisis
GU4911 Seminar in microeconomics
GU4913 Seminar in macroeconomics
GU4918 Seminar in econometrics
BC1003 Introduction to economic reasoning (equivalent to ECON UN1105)
BC1007 Mathematical methods for economics
BC2411 Statistics for economics
BC3014 Entrepreneurship
BC3018 Econometrics
BC3033 Intermediate macroeconomic theory
BC3035 Intermediate microeconomic theory
BC3038 International money and finance

EDUCATION: All courses

ENGINEERING: Only
BMEN E4010 Ethics for biomedical engineers
CHEN E4020 Protection of industrial and intellectual property
EEHS E3900 History of telecommunications

ENGLISH AND COMPARATIVE LITERATURE: All courses

FILM STUDIES: All courses except lab courses, and UN3920 Senior seminar in screenwriting
UN2400 The film medium: script analysis

FRENCH AND ROMANCE PHILOLOGY: All courses

GERMANIC LANGUAGES: All courses

GREEK: All courses

HISTORY: All courses

HISTORY AND PHILOSOPHY OF SCIENCE: All courses

HUMAN RIGHTS: All courses

ITALIAN: All courses

JAZZ STUDIES: All courses

LATIN: All courses

LATINO STUDIES: All courses

LINGUISTICS: All courses except CLLN GU4202

MATHEMATICS: No courses

MEDIEVAL AND RENAISSANCE STUDIES: All courses

MIDDLE EASTERN AND ASIAN LANGUAGE AND CULTURES: All courses

MUSIC: All courses except performance courses, instruction course, and workshops

PHILOSOPHY: All courses except UN401 Introduction to logic
UN3411 Symbolic logic
GU4137 Nonclassical logics
GU4431 Introduction to set theory
GU4424 Modal logic
CSPH GU4801 Mathematical logic I
CSPH GU4802 Incompleteness results in logic
GU4810 Lattices and Boolean algebras
 Colleges in logic

PHYSICAL EDUCATION: No courses

PHYSICS: No courses

POLITICAL SCIENCE: All courses except UN3220 Logic of collective choice
UN3704 Data analysis and statistics for political science research
UN3720 Scope and methods
GU4730 Game theory and political theory
GU4732 Research topics in game theory
GU4791 Advanced topics in quantitative research
GU4792 Advanced topics in quantitative research
GU4700 Math methods for political science

GU4765 Design and analysis of sample surveys
GU4768 Experimental research: design, analysis, and interpretation
GU4710 Principles of quantitative political research
GU4711 Analysis of political data
GU4712 Multivariate political analysis

PSYCHOLOGY: Only
UN1001 The science of psychology
UN2280 Introduction to developmental psychology
All courses on perception, attention, and cognition topics numbered 2200s, 3200s, or 4200s can be taken as nontechnical electives except for PSYC UN2235 and UN4289.
All courses on social, personality, and abnormal numbered 2600s, 3600s, or 4600s can be taken as nontechnical electives.

RELIGION: All courses

SLAVIC LANGUAGES: All courses

SOCIOLOGY: All courses except SOCI UN3020 Social statistics

SPANISH AND PORTUGUESE: All courses

SPEECH: No courses

STATISTICS: No courses

SUSTAINABLE DEVELOPMENT: No courses

URBAN STUDIES: All courses

VISUAL ARTS: No more than one course, which must be at the 3000 level or higher (This is an exception to the workshop rule.)

WOMEN AND GENDER STUDIES: All courses

Music Instruction Courses
Music instruction and performance courses do not count toward the 128 points of credit required for a B.S. degree. Please note that this includes courses taken at Teachers College, Columbia College, and the School of the Arts.

Visual Arts Courses
Students are allowed to take courses in the Visual Arts Department for general credit to be applied toward the B.S. degree. However, no more than one visual arts course, which must be taken at the 3000 level or higher, may count toward the nontechnical elective requirement. This 3000 course is an
exception to the rule that no workshop classes can fulfill the nontech elective requirement.

Technical Course Requirements
The prescribed First-Year/Sophomore Program curriculum requires students to complete a program of technical coursework introducing them to five major areas of technical inquiry: engineering, mathematics, physics, chemistry, and computer science.

All first-year Engineering undergraduate students take ENGI E1102: The art of engineering (4 points). In this course, students see how their high school science and math knowledge can be applied in an engineering context to solve real-world problems through classroom presentations and participation in an in-depth, hands-on project. Along the way, guest lecturers discuss social implications of technology, entrepreneurship, project management, and other important nontechnical issues affecting the practicing engineer.

While students need not officially commit to a particular branch of engineering until the third semester, most programs recommend, and in some cases may require, that particular courses be taken earlier for maximum efficiency in program planning. For information concerning these requirements, students should turn to the individual program sections in this bulletin.

Professional Development
Professional-Level Courses
The courses listed below may be taken by first- and second-year students. Some departments require one of these courses; please consult with departmental charts for more information.

Each course serves as an introduction to the area of study and is taught by department faculty.

The courses are:

**BMEN E1001x Engineering in medicine**  
*Not offered in 2022–2023.*


**CHEN E2100x Introduction to chemical engineering**  
Serves as an introduction to the chemical engineering profession. Students are exposed to concepts used in the analysis of chemical engineering problems. Rigorous analysis of material and energy balances on open and closed systems is emphasized. An introduction to important processes in the chemical and biochemical industries is provided.

**CIVEN E3000y The art of structural design**  
Basic scientific and engineering principles used for the design of buildings, bridges, and other parts of the built infrastructure. Application of these principles to the analysis and design of a number of actual large-scale structures. History of major structural design innovations and the engineers who introduced them. Critical examination of the unique aesthetic/artistic perspectives inherent in structural design. Management, socioeconomic, and ethical issues involved in the design and construction of large-scale structures. Recent developments in sustainable engineering, including green building design and adaptable structural systems.

**EAAE E2100x A better planet by design**  
Introduction to design for a sustainable planet. Scientific understanding of the challenges. Innovative technologies for water, energy, food, materials provision. Multiscale modeling and conceptual framework for understanding environmental, resource, human ecological, and economic impacts and design performance, evaluation. Focus on linkages between planetary, regional, and urban waste, energy, mineral, food, climate, economic, and ecological cycles. Solution strategies for developed and developing country settings.

**ELEN E1201x and y Introduction to electrical engineering**  
Basic concepts of electrical engineering. Exploration of selected topics and their application. Electrical variables, circuit laws, nonlinear and linear elements, ideal and real sources, transducers, operational amplifiers in simple circuits, external behavior of diodes and transistors, first order RC and RL circuits. Digital representation of a signal, digital logic gates, flip-flops. A lab is an integral part of the course.

**MECE E1001x Mechanical engineering: micro-machines to jumbo jets**  
*Not offered in 2022–2023.*

Corequisite(s): MATH UN1101. The role of mechanical engineering in developing many of the fundamental technological advances on which today’s society depends. Topics include airplanes, automobiles, robots, and modern manufacturing methods, as well as the emerging fields of micro-electro-mechanical machines (MEMS) and nanotechnology. The physical concepts that govern the operation of these technologies will be developed from basic principles and then applied in simple design problems. Students will also be exposed to state-of-the art innovations in each case study.

Professional Development and Leadership Program
The Professional Development and Leadership (PDL) program educates students to maximize performance and achieve their full potential to become engineering leaders. Core sessions focus on development of skills and perspectives needed to compete and succeed in a fast-changing technical climate. Topics include professional portfolio (resume, cover letter, business writing, social media presence), communication skills, leadership, ethics, life management (stress, sleep, and time management), and more. Elective sessions include effective presentations, emotional intelligence, data visualization, and interview preparation.

Physical Education
Two terms of physical education (PHED UN1001 or PHED UN1002) are a degree requirement for Columbia Engineering students. No more than 4 points of physical education courses may be counted toward the degree. The physical education requirement can be fulfilled with Barnard dance studio/technique courses. A student who intends to participate in an intercollegiate sport should register for the appropriate section of PHED UN1005: Intercollegiate athletics. Intercollegiate athletes who attend regularly receive 1 point of credit up to a maximum of 4. Student-athletes who leave the team in mid-term but still wish to receive academic credit must notify the Physical Education Office and be placed in another physical education activity to complete the attendance requirement. Students who are advised to follow a restricted or adapted activity program should contact the Director of Physical Education and Recreation. The physical education program offers a variety of activities in the areas of aquatics, fitness, martial arts, individual and dual sports, team sports, and outdoor education. Most activities are designed for the introductory/beginner levels. Intermediate/advanced courses are indicated on the schedule.
Advanced Placement Credit Chart

In order to receive AP credit, students must be in possession of appropriate transcripts or scores and send official score reports to Columbia.

The CEEB code is 2116.

<table>
<thead>
<tr>
<th>Subject</th>
<th>AP Score</th>
<th>AP Credit</th>
<th>Requirements or Placement Status Credit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Art History</td>
<td>5</td>
<td>3</td>
<td>No exemption from HUMA UN1121</td>
</tr>
<tr>
<td>Biology</td>
<td>5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>Chemistry</td>
<td>4 or 5</td>
<td>3</td>
<td>Requires completion of CHEM UN1604 with grade of C or better</td>
</tr>
<tr>
<td></td>
<td>4 or 5</td>
<td>6</td>
<td>Requires completion of CHEM UN2045-UN2046 with grade of C or better</td>
</tr>
<tr>
<td>Computer Science A</td>
<td>4 or 5</td>
<td>3</td>
<td>Exemption from COMS W1004</td>
</tr>
<tr>
<td>Principles</td>
<td>4 or 5</td>
<td>3</td>
<td>Exemption from COMS W1001</td>
</tr>
<tr>
<td>Economics</td>
<td>5 and 4</td>
<td>4*</td>
<td>Exemption from ECON UN1105. Exams must be taken in both micro and macro,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>with a score of 5 in one and at least a 4 in the other.</td>
</tr>
<tr>
<td>English</td>
<td>5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>Language and Composition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Literature and Composition</td>
<td>5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>French</td>
<td>4 or 5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>German</td>
<td>4 or 5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Government and Politics</td>
<td>5</td>
<td>4*</td>
<td>Exemption from POLS UN1201</td>
</tr>
<tr>
<td>United States</td>
<td>5</td>
<td>4*</td>
<td>Exemption from POLS UN1501</td>
</tr>
<tr>
<td>Comparative</td>
<td>5</td>
<td>4*</td>
<td></td>
</tr>
<tr>
<td>History</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>European</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Italian Language</td>
<td>4 or 5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Latin Literature</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Mathematics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculus AB</td>
<td>4 or 5</td>
<td>3</td>
<td>Requires completion of MATH UN1102 with a grade of C or better</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Credit is reduced to 0 if MATH UN1101 is taken.</td>
</tr>
<tr>
<td>Calculus BC</td>
<td>4</td>
<td>3</td>
<td>Requires completion of MATH UN1102 with a grade of C or better</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Credit is reduced to 0 if MATH UN1101 is taken.</td>
</tr>
<tr>
<td>Calculus BC</td>
<td>5</td>
<td>6</td>
<td>Requires completion of APMA E2000 with a grade of C or better</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Credit is reduced to 0 if MATH UN1101 is taken, or to 3 if MATH 1102 is taken.</td>
</tr>
<tr>
<td>Physics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-E&amp;M</td>
<td>4 or 5</td>
<td>3</td>
<td>Maximum of six credits.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Credit is reduced to 0 if PHYS UN1401 or 1601 is taken.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Credit is reduced to 0 if PHYS UN2801 is taken and the final grade is C- or lower.</td>
</tr>
<tr>
<td>C-MECH</td>
<td>4 or 5</td>
<td>3</td>
<td>Credit is reduced to 0 if PHYS UN1401 or 1601 is taken.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Credit is reduced to 0 if PHYS UN2801 is taken and the final grade is C- or lower.</td>
</tr>
<tr>
<td>Physics 1 and 2</td>
<td>4 or 5</td>
<td>3</td>
<td>No exemption. Both AP Physics 1 and 2 must be taken to receive credit.</td>
</tr>
<tr>
<td>Spanish</td>
<td>4 or 5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Language</td>
<td>4 or 5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Literature</td>
<td>4 or 5</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

*AP credits may be applied toward minor requirements depending on the specific rules of the minor. When the rules of the minor allow AP credit to fulfill a requirement, then only one course for a minor may be replaced by advanced placement credit.

**Columbia Engineering students with a 4 or 5 on Calculus AB or a 4 on Calculus BC must begin with MATH UN1101 (Calculus I) or MATH UN1102 (Calculus II). If a Columbia Engineering student with these scores goes directly into APMA E2000 (Multivariable Calculus), they will have to go back and complete MATH UN1102 (Calculus II). Students with A-level or IB calculus credit must start with MATH UN1102 (Calculus II).
The majority of the activities are offered in ten time preferences. Additionally, there are early-morning conditioning activities, Friday-only classes at Baker Athletics Complex, and special courses that utilize off-campus facilities during weekends and vacation periods. The courses offered by the department for each term are included in the online Directory of Classes, and a description of the scheduled activities for each time preference is posted on perec.columbia.edu. Students may only register for one section of physical education each term.

Advanced Placement
Prior to entering Columbia, students may have taken Advanced Placement examinations through the College Entrance Examination Board (CEEB) in a number of technical and nontechnical areas. A maximum of 16 points may be applied. Students may be assigned to an advanced-level course in mathematics or physics based on their AP scores.

In the required pure science areas, the number of advanced placement academic credits awarded to students of engineering and applied science varies from the levels awarded for liberal arts programs, notably in mathematics, physics, chemistry, and computer science. The benefit of advanced placement is acceleration through certain First-Year/Sophomore Program requirements and thus the opportunity of taking specialized courses earlier.

Each year the School reviews the CEEB advanced placement curriculum and makes determinations as to appropriate placements, credit, and/or exemption. Please see the Advanced Placement Credit Chart on p. 12.

International Baccalaureate (IB)
Entering students may be granted 6 points of credit for each score of 6 or 7 on IB Higher Level Examinations if taken in disciplines offered as undergraduate programs at Columbia. Students should consult their adviser at the James H. and Christine Turk Berick Center for Student Advising for further clarification.

British Advanced Level Examinations
Students with grades of A or B on British Advanced Level examinations may be granted 6 points of credit if the examinations were taken in disciplines offered as undergraduate programs at Columbia University. The appropriate transcript should be submitted to the James H. and Christine Turk Berick Center for Student Advising, 403 Lerner.

Other National Systems
Students whose secondary school work was in other national systems, such as the French Baccalauréat, may be granted credit in certain disciplines for sufficiently high scores. The appropriate transcript should be submitted to the James H. and Christine Turk Berick Center for Student Advising, 403 Lerner.

STUDY ABROAD
Engineering today is a global profession. Study abroad allows engineering students to discover the field through the perspective of engineers working in a different language and culture, enabling them to learn the relationship of culture to science and develop the range of transferable skills that employers are seeking today. Study abroad will help students develop intellectually, emotionally, culturally, and socially.

Columbia Engineering undergraduate students can study abroad for either a semester (fall, spring, or summer) or, exceptionally, for a full academic year. Students from every engineering major have studied abroad, and most do so in the spring semester of their sophomore year or in their junior year. Although not a requirement, students are encouraged to have some foreign language skills in order to enhance their cultural competency and their overall study abroad experience.

The Center for Undergraduate Global Engagement will help students identify the appropriate choice for their country of interest and their major. Undergraduate Student Affairs advisers and departmental advisers will help students with their course equivalencies for approved programs so they can graduate on time. Students can take nontechnical electives overseas, or with departmental permission, they may choose technical electives or courses in their major.

It is essential that students begin planning as early as possible. Students are encouraged to meet with advisers in the Center for Undergraduate Global Engagement to review possible global opportunities. Students must obtain approval from their departmental advisers to ensure that their work abroad meets the requirements of their majors, as well as clearance from their Advising Dean in the James H. and Christine Turk Berick Center for Student Advising.

Eligibility Requirements
• Currently enrolled student in good academic and disciplinary standing
• 3.0 GPA
• Making adequate progress toward finishing the first and second year requirements
• Declared a major

Finances
• Fall/Spring (academic year)
  • Billed by Columbia: tuition and health insurance
  • Billed by abroad institution/external vendors: room, board, living and travel expenses
• Summer
  • Student pays most expenses directly to the program and external vendors
  • Not eligible for financial aid

Academic Credit
• Students in Columbia-sponsored programs receive direct Columbia credit, and the courses and grades appear on students’ academic transcripts.
• Credit from approved programs that are not Columbia-sponsored is certified as transfer credit toward the Columbia degree upon successful completion of the program verifiable by academic transcript. Students must earn a grade of C or better in order for credits to be transferred.
• Course titles and grades for approved programs do not appear on the Columbia transcript, and grades are not factored into students’ GPAs.
• Faculty from the Columbia Engineering academic departments
have the responsibility to assess all work completed abroad and make decisions about how these courses fit into major requirements. It is imperative that students gain course-by-course approval from their department prior to departure on a study-abroad program.

**Deadlines**
- Early October: to study abroad during the spring semester
- Early to mid-March: to study abroad during the fall semester or for year-long trips
- Early May: to study abroad during the summer term

For more information on study abroad, students should contact:
Center for Undergraduate Global Engagement
606 Kent Hall, MC 3948
1140 Amsterdam Avenue
New York, NY 10027
212-854-2559
uge@columbia.edu
uge.columbia.edu

SEAS Undergraduate Student Affairs
seasstudyabroad@columbia.edu

**COMBINED PLAN PROGRAMS**
Undergraduate Admissions
212 Hamilton Hall, MC 2807
1130 Amsterdam Avenue
New York, NY 10027
212-854-2522
combinedplan@columbia.edu
undergrad.admissions.columbia.edu/
apply/combined-plan

Columbia Engineering maintains cooperative program relationships with institutions nationwide and with other Columbia University undergraduate divisions. The Combined Plan programs (3-2 and 4-2) allow students to receive a degree both in the liberal arts and in engineering. Combined Plan students complete the requirements for the liberal arts degree along with required prerequisite coursework for their studies in engineering during the three or four years at their liberal arts college before entering the School of Engineering and Applied Science. They then must complete all the requirements for the B.S. degree within four semesters.

**The Combined Plan Program within Columbia University**
Under this plan, the pre-engineering student studies in Columbia College, Barnard College, or the School of General Studies for three or four years, then attends The Fu Foundation School of Engineering and Applied Science for two years, and is awarded the Bachelor of Arts degree and the Bachelor of Science degree in engineering upon completion of the fifth or sixth year. This program is optional at Columbia, but the School recommends it to all students who wish greater enrichment in the liberal arts and pure sciences.

**The Combined Plan with Other Affiliated Colleges**
There are more than one hundred affiliated liberal arts colleges, including those at Columbia, in which a student can enroll in a Combined Plan program leading to two degrees. Each college requires the completion of a specified curriculum, including major and degree requirements, to qualify for the baccalaureate from that institution. Every affiliated school has a liaison officer who coordinates the program at their home institution. Students interested in this program should inform the liaison officer as early as possible, preferably in the first year, in order to receive guidance about completing program requirements. Applicants from nonaffiliated schools are welcome to apply.

Visit the Undergraduate Admissions website for a complete list of affiliated schools, admission application instructions, information on financial aid, and curriculum requirements for Combined Plan program admission. Please note that no change of major is allowed after an admission decision has been rendered.

See page 23 for information on the 4-2 Master of Science Program, BS/MS Program, MS Express Application, and Barnard 4+1 Pathway, which are administered through the Office of Graduate Student Affairs.

**THE JUNIOR-SENIOR PROGRAMS**
Students may review degree progress via DARS (Degree Audit Reporting System) as presented on Student Services Online. Required courses that are not completed are detailed as deficiencies and must be completed during summer session or carried as overload courses in later semesters.

Having chosen their program major in the second semester of their sophomore year, students are assigned to a faculty adviser in the department in which the program is offered. In addition to the courses required by their program, students must continue to satisfy certain distributive requirements, choosing elective courses that provide sufficient content in engineering sciences and engineering design. The order and distribution of the prescribed coursework may be changed with the adviser’s approval. Specific questions concerning course requirements should be addressed to the appropriate department or division. The Vice Dean’s concurrent approval is required for all waivers and substitutions.

**Double Major**
Students who wish to apply for a second major must consult their advising dean about next steps. A proposal to double major must be approved by both departments and then forwarded to the Vice Dean for Undergraduate Programs for a final decision.

Courses cannot be cross-counted between dual majors. Please consult with an adviser and the respective departments to find alternative courses for duplicate requirements.

3-2 students are not eligible to have a second major because of the time constraints of their program.

**Tau Beta Pi**
Tau Beta Pi is the nation’s second-oldest honor society, founded at Lehigh University in 1885. With the creed “Integrity and excellence in engineering,” it is the only engineering honor society representing the entire engineering profession. Columbia’s chapter, New York Alpha, is the ninth oldest and was founded in 1902. Many
Columbia buildings have been named for some of the more prominent chapter alumni: Charles Fredrick Chandler, Michael Idvorsky Pupin, Augustus Schermerhorn, and, of course, Harvey Seeley Mudd.

Undergraduate students whose scholarship places them in the top eighth of their class in their next-to-last year or in the top fifth of their class in their last college year are eligible for membership consideration. These scholastically eligible students are further considered on the basis of personal integrity, breadth of interest both inside and outside engineering, adaptability, and unselfish activity. Benefits of membership include exclusive scholarships and fellowships. Many networking opportunities for jobs and internships are also available, with 230 collegiate chapters and more than 500,000 members in Tau Beta Pi.

**Taking Graduate Courses as an Undergraduate**

With the faculty adviser’s approval, a student may take graduate courses while still an undergraduate in the School. Such work may be credited toward one of the graduate degrees offered by the Engineering Faculty, subject to the following conditions: (1) the course must be accepted as part of an approved graduate program of study; (2) the course must not have been used to fulfill a requirement for the B.S. degree and must be so certified by the Dean; and (3) the amount of graduate credit earned by an undergraduate cannot exceed 15 points. Undergraduates may not take CVN courses.

**The Bachelor of Science Degree**

Students who complete a four-year sequence of prescribed study are awarded the Bachelor of Science degree. The general requirement for the Bachelor of Science degree is the completion of a minimum of 128 academic credits with a minimum cumulative grade-point average (GPA) of 2.0 (C) at the time of graduation. The program requirements, specified elsewhere in this bulletin, include the first-year/sophomore course requirements, the major departmental requirements, and technical and nontechnical elective requirements. Students who wish to transfer points of credit may count no more than 68 transfer points toward the degree and must satisfy the University’s residence requirements by taking at least 60 points of credit while enrolled in The Fu Foundation School of Engineering and Applied Science. Courses may not be repeated for credit unless it is stated otherwise in the course description.

The bachelor’s degree in engineering and applied science earned at Columbia University prepares students to enter a wide range of professions. Students are, however, encouraged to consider graduate work, at least to the master’s degree level, which is increasingly considered necessary for many professional careers.

The Engineering Accreditation Commission (EAC) of ABET, an organization formed by the major engineering professional societies, accredits university engineering programs on a nationwide basis. Completion of an accredited program of study is usually the first step toward a professional engineering license. Advanced study in engineering at a graduate school sometimes presupposes the completion of an accredited program of undergraduate study.

The following undergraduate programs are accredited by the EAC
of ABET: biomedical engineering, chemical engineering, civil engineering, earth and environmental engineering, electrical engineering, and mechanical engineering.

Minors
Columbia Engineering undergraduates may choose to add minors to their programs. This choice should be made in the fall of their sophomore year, when they also decide on a major.

In considering a minor, students must understand that not all minors are available to all students. In addition, the School cannot guarantee that a selected minor can be completed within the usual residence period needed for a major. Indeed, students choosing minors should expect to encounter scheduling difficulties. The potential for the successful completion of a minor depends on the student’s major and the minor chosen, as well as the course schedules and availability, which may change from year to year. The list of minors, as well as their requirements, appear on pages 205–212.

PROGRAMS IN PREPARATION FOR OTHER PROFESSIONS
James H. and Christine Turk Berick Center for Student Advising
403 Lerner Hall, MC 1201
212-854-6378
preprofessional@columbia.edu
cc-seas.columbia.edu/preprofessional/

The Fu Foundation School of Engineering and Applied Science prepares its students to enter any number of graduate programs and professions outside of what is generally thought of as the engineering field. In an increasingly technological society, where the line between humanities and technology is becoming blurred, individuals with a thorough grounding in applied mathematics and the physical and engineering sciences find themselves highly sought after as professionals in practically all fields of endeavor.

Engineering students interested in pursuing graduate work in such areas as architecture, business, education, journalism, or law will find themselves well prepared to meet the generally flexible admissions requirements of most professional schools. Undergraduate students should, however, make careful inquiry into the kinds of specific preparatory work that may be required for admission into highly specialized programs such as medicine.

Premed
Medical, dental, and other health professional schools prefer that undergraduates complete a four-year program of study toward the bachelor’s degree. All health professional schools require prerequisite coursework, but they do not prefer one type of major or scholarly concentration. Students with all types of engineering backgrounds are highly valued.

It is important to note, however, that each medical school in the United States and Canada individually determines its own entrance requirements, including prerequisite coursework and/or competencies. Each medical school also sets its own rules regarding acceptable courses or course equivalents. It is therefore essential that students plan early and confirm the premedical requirements for those schools to which they intend to apply. The Engineering curriculum covers many of the prerequisite courses required by medical schools; however, in addition to completing the mathematics, chemistry, and physics courses required by the First-Year/Sophomore Program, most schools ask for a full year of organic chemistry, a full year of biology, a full year of English, a semester of statistics, and a semester of biochemistry. Advanced Placement credit is accepted in fulfillment of these requirements by some schools but not all. Students are responsible for monitoring the requirements of each school to which they intend to apply.

Generally, students with Advanced Placement credit are strongly advised to take further courses in the field in which they have received such credit.

In addition to medical school requirements, all medical schools currently require applicants to sit for the Medical College Admissions Test (MCAT). The recommended preparation for this exam is:

• One year of general chemistry and general chemistry lab
• One year of organic chemistry and organic chemistry lab
• One year of introductory biology and biology lab
• One semester of biochemistry
• One year of general physics and physics lab
• One semester of introductory psychology

As you prepare for this path, you should consult regularly with both your assigned adviser and one of the premedical advisers in the James H. Christine Turk Berick Center for Student Advising. These individuals will help to guide you in your course selection and planning, and introduce you to extracurricular and research opportunities related to your interests in health and medicine. Preprofessional Advising maintains an online list of many different clinical volunteer and research opportunities across New York City and beyond. Exploration of the career and sustained interactions with patients is viewed by many medical schools as essential preparation, and therefore students are strongly encouraged to spend time volunteering/working in clinical and research environments before applying to medical school.

Students must apply for admission to health professional schools more than one year in advance of the entry date. Students who are interested in going directly on to health professional schools following graduation should complete all prerequisite courses required for the MCAT by the end of the junior year. It is entirely acceptable (and most common) for students to take time between undergraduate and health professional school and thus delay application to these schools for one or more years. Students planning to apply to medical or dental school should be evaluated by the Premedical Advisory Committee prior to application. A Premedical Advisory Committee application is made available each year in December. For more information regarding this process and other premedical-related questions, please consult with a premedical adviser in the Berick Center for Student Advising or peruse its website: www.cc-seas.columbia.edu/preprofessional/health/.
Urban Teaching: New York State Initial Certification in Adolescence Education Grades 7–12 for Teachers of Mathematics and the Sciences or in Elementary Education Grades 1–6

The Barnard Education Program provides courses leading to certification to teach in New York State (with reciprocal agreements with 41 other states) at either the elementary or secondary level. Students gain experience and develop skills in urban school classrooms. Required coursework includes psychology and education, a practicum, and student teaching, totaling 23–26 points of credit depending on the level of certification sought.

Certification to teach mathematics requires 36 points in mathematics. Pure science courses required are: 36 points in the sciences, of which 18 must be in the area of the certification sought: chemistry, biology, physics, or earth science.

The deadline for application, which includes an essay and letters of recommendation, is the first Monday in March of the student’s sophomore year. This allows program faculty to support students through program planning to ensure that students can meet the requirements for certification. However, when space allows, applications will be considered through the fall of the junior year. Applications from juniors are due no later than the first Monday in October. Students who plan to study abroad during the spring of their junior year should apply during the fall semester of their sophomore year. Students should decide on their interest in teacher certification by the end of the first year in order to start coursework in the sophomore year.

JOINT PROGRAMS

The 4-1 Program at Columbia College

Students who are admitted as first-year students to the School of Engineering and Applied Science and subsequently complete the four-year program for the Bachelor of Science degree have the opportunity to apply for admission to either Columbia College or Barnard College and, after one additional year of study, receive the Bachelor of Arts degree. The fifth year of study begins in the fall semester, and students are required to complete two full-time semesters in the College totaling at least 31 points.

The program is selective, and admission is based on the following factors: granting of the B.S. at Columbia Engineering at the end of the fourth year; fulfillment of all College Core requirements by the end of the fourth year at the School; a minimum GPA of 3.0 in the College Core and other courses; and the successful completion of any prerequisites for the College major or concentration. Students apply at the end of their junior year at the School; to be admitted to the program, students need to have a plan in place to complete the College major or concentration by the end of their fifth year.

Interested students should contact their advising dean for further information.

School of International and Public Affairs

The Fu Foundation School of Engineering and Applied Science and the School of International and Public Affairs offer a joint program enabling a small number of students to complete the requirements for the degrees of Bachelor of Science and Master of International Affairs in five years instead of six. Not only an excellent academic record but also maturity, fluency in an appropriate foreign language, and pertinent experience will determine admission to this program. For more information, please contact your advising dean.

UNDERGRADUATE ADMISSIONS

For information about undergraduate admissions, please visit the Undergraduate Admissions website or contact the office by phone or email. See page 28 for information about graduate admissions, including combined undergraduate/graduate programs.
The 2022–2023 tuition and fees are estimated. Tuition and fees are prescribed by statute and are subject to change at the discretion of the Trustees.

University charges such as tuition, fees, and residence hall and meal plans are billed in the first Student Account Statement of the term, which is sent out in July and December of each year for the upcoming term. This account is payable and due in full on or before the payment due date announced in the Statement, typically at the end of August or early January before the beginning of the billed term. Any student who does not receive the first Student Account Statement is expected to pay at registration.

If the University does not receive the full amount due for the term on or before the payment due date of the first Statement, a late payment charge of $150 will be assessed. An additional charge of 1.5 percent per billing cycle may be imposed on any amount past due thereafter.

Students with an overdue account balance may be prohibited from registering, changing programs, or obtaining a diploma or transcripts. In the case of persistently delinquent accounts, the University may utilize the services of an attorney and/or collection agent to collect any amount past due.

Students may need to add another $100 to $300 for drafting materials or laboratory fees in certain courses. Each student taking laboratory courses

**TUITION**

Undergraduate students enrolled in the Fu Foundation School of Engineering and Applied Science pay a flat tuition charge of $31,285 per term, regardless of the number of course credits taken. Postgraduate special students and degree candidates enrolled for a ninth term are billed according to the per-point system; the per-point cost is $2,092.

**MANDATORY FEES**

- Orientation fee: $510 (one-time charge in the first term of registration)
- Student Life fee: $823 per term
- Health and Related Services fee: $654 per term
- International Services charge: $135 per term (international students only)
- Document fee: $105 (one-time charge)

**OTHER FEES**

Application and late fees:
- Application for undergraduate admission: $85
- Application for undergraduate transfer admission: $85
- Late registration fee during late registration: $50; after late registration: $100

Books and course materials: Depends upon course

Laboratory fees: See course listings

Room and board (estimated): $16,156

**HEALTH INSURANCE**

Columbia University offers the Student Medical Insurance Plan, which provides both Basic and Comprehensive levels of coverage. Full-time students are automatically enrolled in the Basic level of the Plan and billed for the insurance premium in addition to the Health Service fee. Visit the Columbia Health website at health.columbia.edu for detailed information about medical insurance coverage options and directions for making confirmation, enrollment, or waiver requests.

**PERSONAL EXPENSES**

Students should expect to incur miscellaneous personal expenses for such items as clothing, linen, laundry, dry cleaning, and so forth. Students should also add to the above expenses the cost of two round trips between home and the University to cover travel during the summer and the month-long, midyear break.

The University advises students to open a local bank account upon arrival in New York City. Since it often takes as long as three weeks for the first deposit to clear, students should plan to cover immediate expenses using either a credit card, traveler’s checks, or cash draft drawn on a local bank. Students are urged not to arrive in New York without sufficient start-up funds.

**LABORATORY CHARGES**

Students may need to add another $100 to $300 for drafting materials or laboratory fees in certain courses. Each student taking laboratory courses
must furnish, at their own expense, the necessary notebooks, blank forms, and similar supplies. In some laboratory courses, a fee is charged to cover expendable materials and equipment maintenance. Students engaged in special tests, investigations, theses, or research work are required to meet the costs of expendable materials as may be necessary for this work and in accordance with such arrangements as may be made between the student and the department immediately concerned.

DAMAGES

All students will be charged for damage to instruments or apparatus caused by their carelessness. The amount of the charge will be the actual cost of repair, and, if the damage results in total loss of the apparatus, adjustment will be made in the charge for age or condition. To ensure that there may be no question as to the liability for damage, students should note whether the apparatus is in good condition before use and, in case of difficulty, request instruction in its proper operation. Where there is danger of costly damage, an instructor should be requested to inspect the apparatus. Liability for breakage will be decided by the instructor in charge of the course.

When the laboratory work is done by a group, charges for breakage will be divided among the members of the group. The students responsible for any damage will be notified that a charge is being made against them. The amount of the charge will be stated at that time or as soon as it can be determined.

TUITION AND FEE REFUNDS

Students who make a complete withdrawal from a term are assessed a withdrawal fee of $75. Late fees, application fees, withdrawal fees, tuition deposits, special fees, computer fees, special examination fees, and transcript fees are not refundable.

The Health Service Fee, Health Insurance Premium, University facilities fees, and student activity fees are not refundable.

Students who withdraw within the first 60 percent of the academic period are subject to a refund calculation, which refunds a portion of tuition based on the percentage of the term remaining after the time of withdrawal. This calculation is made from the date the student’s written notice of withdrawal is received by the Dean’s Office.

Percentage Refund for Withdrawal during First Nine Weeks of Term

Prorated for calendars of a different duration:

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<tr>
<th>Week</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>1st week</td>
<td>100%</td>
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<tr>
<td>2nd week</td>
<td>100%</td>
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<tr>
<td>3rd week</td>
<td>90%</td>
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<td>4th week</td>
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<td>5th week</td>
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<td>6th week</td>
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<td>8th week</td>
<td>40%</td>
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<td>9th week and after</td>
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</tbody>
</table>

For students receiving federal student aid, refunds will be made to the federal aid programs in accordance with Department of Education regulations.

Refunds will be credited in the following order:
Federal Unsubsidized Stafford Loans
Federal Stafford Loans
Federal Perkins Loans
Federal PLUS Loans (when disbursed through the University)
Federal Pell Grants
Federal Supplemental Educational Opportunity Grants
Other Title IV funds

Withdrawing students should be aware that they will not be entitled to any portion of a refund until all Title IV programs are credited and all outstanding charges have been paid.
Financial Aid and Educational Financing
618 Lerner Hall
2920 Broadway
Mailing: 100 Hamilton Hall, MC 2802
1130 Amsterdam Avenue
New York, NY 10027
Monday–Friday: 9:00 a.m.–5:00 p.m.

Phone: 212-854-3711
Fax: 212-854-5353
ugrad-finaid@columbia.edu
cc-seas.financialaid.columbia.edu

Columbia is committed to meeting the full demonstrated financial need for all applicants admitted as first-year students or transfer students pursuing their first degree. Financial aid is available for all four undergraduate years, provided that students continue to demonstrate financial need.

All applicants who are citizens or permanent residents of the United States, who are granted refugee visas by the United States, or who are undocumented students in the United States are considered for admission in a need-blind manner.

International students who did not apply for financial aid in their first year are not eligible to apply for financial aid in any subsequent years. Foreign transfer candidates applying for aid must understand that such aid is awarded on an extremely limited basis. Columbia does not give any scholarships for academic, athletic, or artistic merit.

Please visit the Financial Aid website at cc-seas.financialaid.columbia.edu/ for more information on financial aid, including requirements and application instructions.

Satisfactory Academic Progress
Columbia University complies with federal SAP regulations. To be eligible for Federal Student Aid (Federal Pell Grant, Federal SEOG, Federal Work-Study, Federal Perkins Loan, Federal Direct/PLUS loan), an otherwise eligible student must meet or exceed the SAP standards set by their school or program at the time SAP is assessed. The SAP policy may be found online at sfs.columbia.edu/central-sap-policy.
Graduate Studies
Graduate programs of study in The Fu Foundation School of Engineering and Applied Science are not formally prescribed, but are planned to meet the particular needs and interests of each individual student. Departmental requirements for each degree, which supplement the general requirements given below, appear in the sections on individual graduate programs.

Applicants for a graduate program are required to have completed an undergraduate degree and to furnish an official transcript as part of the admissions application. Ordinarily, the candidate for a graduate degree will have completed an undergraduate course in the same field of engineering in which they seek a graduate degree. However, if the student's interests have changed, it may be necessary to make up such basic undergraduate courses as are essential to graduate study in their new field of interest.

A maximum of 15 points of credit of graduate-level coursework completed at Columbia University, before the new program is approved and not used toward another degree, may be counted toward the degree. Students registered in the School have a minimum requirement for each Columbia degree of 30 points of credit of coursework completed at Columbia University. The student must enroll for at least 15 of these points while registered as a matriculating student in a degree program in the Engineering School. (See also the section Nondegree Students and the chapter Columbia Video Network.) Students wishing to change from the Ph.D. degree to the Eng.Sc.D. degree must therefore enroll for at least 15 points while registered in the School. For residence requirements for students registered in the Graduate School of Arts and Sciences or those wishing to change from the Eng.Sc.D. degree to the Ph.D. degree, see the bulletin of the Graduate School of Arts and Sciences.

Students admitted to graduate study are expected to enter upon the term for which they are admitted and continue their studies in each succeeding regular term of the academic year. Any student who fails to register for the following term will be assumed to have withdrawn unless a leave of absence has been granted by the Office of Graduate Student Affairs.

While many candidates study on a full-time basis, it is usually possible to obtain all or a substantial part of the credit requirement for the master's or Eng.Sc.D. degrees through part-time study.

Under special conditions, and with the prior approval of the department of their major interest and of the Assistant Dean, a student may be permitted to take a required subject at another school. However, credit for such courses will not reduce the 30-point minimum that must be taken at Columbia University.

For graduation, a candidate for any degree except a doctoral degree must file an Application for Degree or Certificate on the date specified in the Academic Calendar. Candidates for a doctoral degree must apply for the final examination. If the degree is not earned by the next regular time for the issuance of diplomas subsequent to the date of filing, the application must be renewed. Degrees are awarded three times a year—in October, February, and May.

THE MASTER OF SCIENCE DEGREE

The Master of Science degree is offered in many fields of engineering and applied science upon the satisfactory completion of a minimum of 30 points of credit of approved graduate study extending over at least one academic year.

While a suitable Master of Science program will necessarily emphasize some specialization, the program should be well balanced, including basic subjects of broad importance as well as theory and applications. The history of modern economic, social, and political institutions is important in engineering, and this is recognized in the prescribed undergraduate program of the School. If the candidate's undergraduate education has been largely confined to pure science and technology, a program of general studies, totaling from 6 to 8 points, may be required. Supplementary statements covering these special requirements are issued by the School's separate departments. An applicant who lacks essential training will be required to strengthen or supplement the undergraduate work by taking or repeating certain undergraduate courses before proceeding to graduate study. No graduate credit (that is, credit toward the minimum 30-point requirement for the Master of Science degree) will be allowed for such
modules are tailored for each stage of the doctoral program, with a focus on the development of academic, research, and professional skills. Students will also have the opportunity to participate in small group communication workshops for doctoral students and individualized coaching tailored to their specific goals. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

The 4-2 Master of Science Program

The 4-2 Master of Science Program provides the opportunity for students holding bachelor’s degrees from affiliated liberal arts colleges (see the listing under the heading The Combined Plan Program with Other Affiliate Colleges) with majors in mathematics, physics, chemistry, or certain other physical sciences to receive the M.S. degree after two years of study at Columbia in the following fields of engineering and applied science: biomedical, chemical, civil, earth and environmental, electrical, industrial, and mechanical engineering; applied physics; applied mathematics; computer science; engineering mechanics; operations research; and materials science.

Each applicant must produce evidence of an outstanding undergraduate record, including superior performance in physics and mathematics through differential equations. The program of study will be individually designed in consultation with a faculty adviser and will integrate undergraduate work with the field of engineering or applied science the student chooses to follow. During the first year, the program will consist primarily of basic undergraduate courses; during the second year, of graduate courses in the selected field. The student must complete at least 30 credits of graduate study to qualify for the degree.

A student whose background may require supplementary preparation in some specific area, or who has been out of school for a considerable period, will have to carry a heavier than normal course load or extend the program beyond two years.

Graduates of the 4-2 Master of Science program may not be eligible to take the Fundamentals of Engineering (FE) exam if their undergraduate degree is not in engineering or a related field. Students should also check with individual state boards to determine eligibility requirements for employment.

Please contact the Office of Graduate Student Affairs, The Fu Foundation School of Engineering and Applied Science, 530 S. W. Mudd, MC 4718, 500 West 120th Street, New York, NY 10027; you should also contact your home institution’s Combined Plan liaison for program information. You may, in addition, email questions to seasgradmit@columbia.edu.

Dual Degree Program in Computer Science with the School of Journalism

The School of Journalism and the Engineering School offer a dual degree program leading to the degrees of Master of Science in Journalism and the Master of Science in Computer Science. (See Computer Science.)

Dual Degree Program in Industrial Engineering with Columbia Business School

Columbia Business School and the Engineering School offer a joint program leading to the degrees of Master of Business Administration and Master of Science in Industrial Engineering. (See Industrial Engineering and Operations Research.)

Master of Science Program in Management Science and Engineering

In collaboration with Columbia Business School’s Decision, Risk and Operations Division, the Industrial Engineering and Operations Research department offers a master’s degree program focused on management and engineering perspectives in solving problems of complex systems. (See Industrial Engineering and Operations Research.)

Master of Science Program in Business Analytics

In partnership with Columbia Business School’s Decision, Risk and Operations Division and Marketing Division, the Industrial Engineering and Operations Research department offers a master’s
degree program designed for those who want to focus on learning the modeling techniques and data science tools that help businesses use data to make better decisions. (See Industrial Engineering and Operations Research.)

Master of Science in Data Science
Offered by the Engineering School (jointly between the Department of Computer Science and the Department of Industrial Engineering and Operations Research), in partnership with the Graduate School of Arts and Sciences (the Department of Statistics), the M.S. in Data Science allows students to apply data science techniques to their field of interest.

Candidates for the Master of Science in Data Science are required to complete a minimum of 30 graduate-level credits, which includes seven required courses: Algorithms for Data Science, Machine Learning for Data Science, Exploratory Data Analysis and Visualization, Probability and Statistics for Data Science, Statistical Inference & Modeling, Computer Systems for Data Science, and Data Science Capstone & Ethics. A minimum of 9 credits of elective coursework are chosen in consultation with the student’s adviser and should be technical in nature and must be a 4000-level graduate course or higher that expands the student’s expertise in data science. M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement.

Certificate of Professional Achievement in Data Science
Graduate Online delivery is also available for this program. Candidates for the Certificate of Professional Achievement in Data Science, a nondegree part-time program, are required to complete a minimum of 12 credits, including four required courses: Algorithms for Data Science, Probability and Statistics for Data Science, Machine Learning for Data Science, and Exploratory Data Analysis and Visualization.

DOCTORAL DEGREES:
ENG.S.C.D. AND PH.D.
Two doctoral degrees in engineering are offered by the University: the Doctor of Engineering Science, administered by The Fu Foundation School of Engineering and Applied Science, and the Doctor of Philosophy, administered by the Graduate School of Arts and Sciences. Both doctoral programs are subject to review by the Committee on Instruction of the School. Doctoral students must submit a petition to the Office of Graduate Student Affairs to change from the Eng.Sc.D. degree to the Ph.D. degree or from the Ph.D. degree to the Eng.Sc.D. degree. The petition must be submitted within the first year of enrollment in the doctoral program. Any petitions submitted after this period will not be considered.

Doctoral degree status can be changed only once; students, therefore, must determine which doctoral degree program is most appropriate for their academic and professional endeavors.

Departmental requirements may include comprehensive written and oral qualifying examinations. A student must have a satisfactory grade-point average to be admitted to the doctoral qualifying examination. Thereafter, the student must write a dissertation embodying original research under the sponsorship of a member of their department and submit it to the department. If the department recommends the dissertation for defense, the student applies for final examination, which is held before an examining committee approved by the appropriate Dean's Office. This application must be made at least three weeks before the date of the final examination.

The defense of the dissertation constitutes the final test of the candidate’s qualifications. It must be demonstrated that the candidate has made a contribution to knowledge in a chosen area. In content the dissertation should, therefore, be a distinctly original contribution in the selected field of study. In form it must show the mastery of written English, which is expected of a university graduate.

For the Ph.D. Degree
A student must obtain the master’s degree (M.S.) before enrolling as a candidate for the Ph.D. degree. Application for admission as a doctoral candidate may be made while a student is enrolled as a master’s degree candidate. Candidates for the Ph.D. degree must register full time and complete six Residence Units. The minimum requirement in coursework for the doctoral degree is 60 points of credit beyond the bachelor’s degree. A master's degree from an accredited institution may be accepted in the form of advanced standing as the equivalent of one year of residence (30 points of credit and two Residence Units). An application for advanced standing must be completed during the first semester of study. Ph.D. candidates will be required to complete a minimum of 30 additional points of credit in residence for a letter grade beyond the M.S.

Ph.D. candidates should obtain a copy of the bulletin of the Graduate School of Arts and Sciences, in which are printed the requirements of the department of major interest.

For the Eng.Sc.D. Degree
A student must obtain the master’s degree (M.S.) before enrolling as a candidate for the Eng.Sc.D. degree. The minimum requirement in coursework for the doctoral degree is 60 points of credit beyond the bachelor’s degree. Eng.Sc.D. candidates will be required to complete a minimum of 30 additional points of credit in residence beyond the M.S. for a letter grade. A master’s degree from an accredited institution may be accepted in the form of advanced standing as the equivalent of 30 points of credit. Candidates for the Eng.Sc.D. degree must, in addition to the 60-point requirement, accumulate 12 points of credit in the departmental course E9800: Doctoral research instruction (see below). The candidate for the degree of Doctor of Engineering Science must submit evidence that their dissertation has been filed in compliance with requirements set by the faculty of Engineering and Applied Science.

Doctoral Research Instruction
An Eng.Sc.D. candidate is required to complete 12 credits in the departmental course E9800: Doctoral research instruction in accordance with the
following guidelines:
1. After obtaining a master’s degree or advanced standing, at which time the student begins doctoral research, the student is eligible to register for E9800 (3, 6, 9, or 12 points of credit per term).
2. Registration for E9800 at a time other than that prescribed above is not permitted, except by written permission of the Dean.
3. The 12 points of E9800 required for the Eng.Sc.D. degree do not count toward the minimum residence requirements, e.g., 30 points beyond the master’s degree or 60 points beyond the bachelor’s degree.
4. If a student is required to take coursework beyond the minimum residence requirements, the 12 points of doctoral research instruction must still be taken in addition to the required coursework.
5. A student must register continuously through the fall and the spring terms. This requirement does not include the summer session.

**Completion of Requirements**
The requirements for the Eng.Sc.D. degree must be completed in no more than seven years. The seven-year time period begins at the time of enrollment and extends to the date on which the dissertation defense is held.

Extension of the time allowed for completion of the degree may be granted on recommendation of the student’s sponsor and the department chair to the Dean when special circumstances warrant. Such extensions are initiated by submitting a statement of work in progress and a schedule for completion together with the sponsor’s recommendation to the department chair.

Please contact the Office of Graduate Student Affairs for more information.

**NONDEGREE STUDENTS**
Qualified persons who are not interested in a degree program but who wish only to take certain courses may be permitted to register as nondegree students, provided facilities are available.

Many graduate courses in The Fu Foundation School of Engineering and Applied Science are offered in the late afternoon and evening in order to make them available to working individuals who wish to further their knowledge in the areas of engineering and applied science. Individuals who find it difficult or impossible to attend classes on the Columbia campus may be able to receive instruction from the School through the Columbia Video Network without leaving their worksites. Individuals interested in this program should read the section describing the distance learning Columbia Video Network (CVN), which follows in this bulletin.

Nondegree students receive grades and must maintain satisfactory attendance and performance in classes or laboratories and will be subject to the same rules as degree candidates. Should a nondegree student decide to pursue a degree program, work completed as a nondegree student may be considered for advanced standing, but no more than 15 points of coursework completed as a nondegree student may be counted toward a graduate degree.

For additional information and regulations pertaining to nondegree students, see Graduate Admissions.

**OFFICE OF GRADUATE STUDENT AFFAIRS**
The Office of Graduate Student Affairs at The Fu Foundation School of Engineering and Applied Science is integral to the School’s teaching, research, and service mission and works to enhance the educational opportunities available to students. This office provides leadership for the integration of educational programs and services that enhance recruitment, retention, and quality of campus life for graduate students at Columbia Engineering. It strives to demonstrate sensitivity and concern in addressing the needs of the School’s population. The office is dedicated to providing service to prospective, new, and continuing students pursuing a graduate education in engineering or applied science.
BACKGROUND
Columbia University’s Fu Foundation School of Engineering and Applied Science established the Columbia Video Network (CVN) in 1986 to meet a growing need within the engineering community for a graduate distance education program. More than 30 years later, our part-time fully online programs provide working professionals high quality graduate engineering education in a convenient and flexible format.

PROGRAM BENEFITS
At CVN, the #1 ranked Best Graduate Online Engineering Program by the 2022 U.S. News & World Report, students can enroll in online courses and earn graduate engineering degrees without ever having to set foot on campus. CVN courses are taught by Columbia University faculty, offering students flexibility coupled with the high-caliber teaching, resources, and standards inherent in The Fu Foundation School of Engineering and Applied Science.

CVN students take graduate-level courses that are identical in curriculum and rigor to those offered to on-campus students. CVN courses are taught by the same faculty that teach on-campus courses. Students have access to online University resources and are a part of the Columbia community.

CVN graduates earn the same degrees as on-campus students. CVN’s administrative staff is available to assist with registration procedures and technical queries. Students pursuing their M.S. and DES are assigned an academic adviser.

PROGRAMS OF STUDY
CVN offers part-time online graduate degrees, certificates, and nondegree courses. CVN students may enroll in select SEAS graduate courses in fall, spring, and summer terms. CVN administrators work closely with faculty members from each department to select courses that best fit the needs of our students.

Master of Science (M.S.) Degree Programs
The M.S. is a coursework-based master’s, which requires 30 credits of online coursework. The M.S. must be completed within five years. Students are required to maintain continuous enrollment, which is a minimum of two classes per year, one in the fall and one in the spring semesters.

Fields of Study:
- Applied Mathematics
- Applied Physics
- Biomedical Engineering
- Chemical Engineering
- Civil Engineering
- Computer Science (9 tracks)
  - Computational Biology
  - Computer Security
  - Foundations of Computer Science
  - Machine Learning
  - Natural Language Processing
  - Network Systems
  - Personalized Track
  - Software Systems
  - Vision Graphics, Interactions, and Robotics
- Earth and Environmental Engineering
- Electrical Engineering
- Industrial Engineering: Systems Engineering
- Materials Science and Engineering
- Mechanical Engineering
- Operations Research: Methods in Finance

M.S. Application
The M.S. application requires a minimum cumulative undergraduate GPA of 3.0, a resume/CV, a 250-word personal/professional statement, an unofficial transcript for each university attended, three letters of recommendation, self-reported GRE General Test scores (GRE scores are valid for five years), TOEFL/IELTS scores (if applicable), and a $150 application fee. Applications are reviewed on a rolling basis, and decisions are issued four to six weeks after submission. Applications must be submitted via the application portal on cvn.columbia.edu.

Accepted students can begin coursework up to one year after admission into CVN.
Doctor of Engineering Science (DES) Degree Programs
The DES can be completed partially online. Students in the program can complete some of their courses online. Students also perform research on campus with a faculty adviser. Applicants must already have an M.S. in a related field prior to applying to the DES program. The DES must be completed within seven years. Applicants must select their faculty advisers prior to submitting their applications.

Fields of Study:
• Earth and Environmental Engineering
• Electrical Engineering
• Mechanical Engineering

DES Application
The DES application requires a minimum cumulative undergraduate GPA of 3.0, an M.S. in a related field, a resume/CV, a 250-word personal/professional statement, an unofficial transcript for each university attended, three letters of recommendation, self-reported GRE General Test scores (GRE scores are valid for five years), TOEFL/IELTS scores (if applicable), a $150 application fee, and the name of a prospective faculty adviser. Applications must be submitted via the application portal on cvn.columbia.edu. Applications are reviewed on a rolling basis, and decisions are issued four to six weeks after submission.

Certification of Professional Achievement Programs
CVN offers 12-credit, four-course Certification of Professional Achievement programs in various fields for those who desire graduate-level coursework for professional advancement. Up to six credits earned in the Certification of Professional Achievement program can be applied towards an M.S. degree at CVN. Students enrolled in the certificate program must complete the program within two years and earn a GPA of 3.0 or higher. Completion of the certification does not guarantee acceptance into a degree program.

Fields of Study:
• Applied Mathematics
• Business and Technology
• Civil Engineering
• Construction Management
• Data Science
• Earth and Environmental Engineering
• Electrical Engineering
• Financial Engineering
• Industrial Engineering
• Information Systems
• Low Carbon and Efficiency Technology
• Manufacturing Engineering
• Materials Science
• Multimedia Networking
• Nanotechnology
• Networking and Systems
• New Media Engineering
• Operations Research
• Sustainable Energy
• Systems Engineering
• Telecommunications
• Wireless and Mobile Communications

Certification Application
The certification application requires a minimum cumulative undergraduate GPA of 3.0, a resume/CV, a 250-word personal/professional statement, an unofficial transcript for each university attended, three letters of recommendation, and a $150 application fee. Applications are reviewed on a rolling basis, and decisions are issued within a week of submission. Applications must be submitted via the application portal on cvn.columbia.edu.

Nondegree Courses
Students who have earned an undergraduate degree in engineering, mathematics, or a related field may take one or two courses as a nondegree student. Any of the CVN courses listed on the CVN website may be taken as a nondegree course, provided that the student has met the prerequisites for that course.

Up to six credits earned as a nondegree student may be applied towards the M.S. course requirements. Earning credit as a nondegree student does not guarantee acceptance into a degree program.

Nondegree Application
The application requires a minimum cumulative undergraduate GPA of 3.0, a resume/CV, a 250-word personal/professional statement, and unofficial transcripts from every university attended. There is no application fee. Applications are reviewed on a rolling basis, and decisions are issued within a week of submission. Applications must be submitted via the application portal on cvn.columbia.edu.
The basic requirement for admission as a graduate student is a bachelor’s degree received from an institution of acceptable standing. Ordinarily, the applicant will have majored in the field in which graduate study is intended, but in certain programs, preparation in a related field of engineering or science is acceptable. The applicant will be admitted only if the undergraduate record shows promise of productive and effective graduate work.

Students who hold an appropriate degree in engineering may apply for admission to study for the Ph.D. degree. However, students are required to obtain the master’s degree first. Students currently enrolled in the School’s M.S. program may apply for admission to the doctoral program after completing 15 points of coursework. Completion of a relevant master’s degree is required prior to entry into the Ph.D. program.

Students may be admitted in one of the following five classifications: candidate for the M.S. degree, candidate for the M.S. degree leading to the Ph.D. degree, candidate for the Doctor of Engineering Science degree, candidate for the Doctor of Philosophy degree (see also the bulletin of the Graduate School of Arts and Sciences), or nondegree student (not a degree candidate). Note: Not more than 15 points of credit completed as a nondegree student may be counted toward a degree.

The applicant must submit all materials directly, not through an agent or third-party vendor, with the sole exception of submissions by the U.S. Department of State’s Fulbright Program and its three partner agencies: IIE, LASPAU and AMIDEAST, and by the Danish-American Fulbright Commission (DAF), Deutscher Akademischer Austauschdienst (DAAD), and Vietnam Education Fund (VEF). In addition, the applicant will be required to attest to the accuracy and authenticity of all information and documents submitted to Columbia. If you have any questions about this requirement, please contact the admissions office at seasgradmit@columbia.edu.

Academic integrity is the cornerstone of a university education. Failure to submit complete, accurate, and authentic application documents consistent with these instructions may result in denial or revocation of admission, cancellation of academic credit, suspension, expulsion, or eventual revocation of degree. Applicants may be required to assist admissions staff and faculty involved in admission reviews in the verification of all documents and statements made in documents submitted by students as part of the application review process.

## APPLICATION REQUIREMENTS

Applicants can only apply to one degree program per admission term. Applicants must submit an online application and required supplemental materials, as described below. An official transcript from each postsecondary institution attended, personal statement, and resume or curriculum vitae must be submitted. Consideration for admission will be based not only on the completion of an earlier course of study, but also upon the quality of the record presented and upon such evidence as can be obtained concerning the applicant’s personal fitness to pursue professional work.

Additionally, applicants must provide three letters of recommendation and the results of required standardized exams. The Graduate Record Examination (general) is required for all candidates. Applicants to the doctoral program in applied physics are also required to submit official GRE Physics Test scores. GRE general and subject test scores are valid for five years from the test administration date according to the Educational Testing Service (ETS). English language test scores are required of all applicants who received their bachelor’s degree in a country in which English is not the official and widely spoken language. The Test of English as a Foreign Language (TOEFL), International English Language Testing System (IELTS), Duolingo English Test (DET), or Pearson Test of English (PTE) scores satisfy the test requirement and are valid for two years according to the test organizations.
Applicants may be asked to participate in an interview as part of the application process.

ENGLISH PROFICIENCY
The Office of Graduate Student Affairs no longer requires students to demonstrate English proficiency as a graduation requirement at The Fu Foundation School of Engineering and Applied Science. Regardless of TOEFL, IELTS, DET, or PTE scores submitted for admission, students should continue to work on maintaining adequate verbal and/or written abilities for successful integration within their classes and future professional endeavors. Students are highly encouraged to be proactive about addressing their English proficiency by utilizing the many resources available within Columbia University and throughout New York City.

Students have the option of enrolling in communication courses offered through Columbia Engineering’s Professional Development and Leadership courses (noncredit, tuition free) and the American Language Program (ALP) at Columbia University (credited). Course credits earned through ALP, however, do not count toward the minimum engineering academic coursework requirements. Enrollment in ALP courses is solely the financial responsibility of the student. As a rule, ISSO will not permit students to drop courses or fall below full-time registration for language proficiency deficiencies.

APPLICATION FEE
The nonrefundable application fee for all graduate degree and nondegree programs is $85.

GRADUATE ADMISSION CALENDAR
Applicants are admitted twice yearly, for the fall and spring semesters.
- Fall admission application deadlines: December 15 for Ph.D., Eng.Sc.D., and M.S. leading to Ph.D. programs and February 15 for most M.S. only and nondegree applicants. Please visit the Office of Graduate Student Affairs website for specific M.S. only program deadlines.
- Spring admission application deadline: October 1 for all departments and degree levels.

Applicants who wish to be considered for scholarships, fellowships, and assistantships should file complete applications for fall admission.

EXPRESS APPLICATION
Columbia Engineering, Columbia College, General Studies, and Barnard seniors as well as alumni from the same schools, who have graduated within three years, may be eligible to apply to a master's program using the express application process. A minimum cumulative GPA of 3.5 in an approved undergraduate program is required to be eligible to submit an M.S. Express application. For more information about eligibility, visit the Office of Graduate Student Affairs website.

The M.S. Express online application, which waives the submission of GRE scores, letters of recommendation, and official transcripts, streamlines and simplifies the application process for graduate study. Contact your academic department or the Office of Graduate Student Affairs for further details.

BS/MS APPLICATION
The Integrated BS/MS Program is offered in Biomedical Engineering, Electrical Engineering, and Mechanical Engineering. The program is open only to Columbia University juniors with a cumulative GPA of 3.4. After earning the BS degree, students are able to seamlessly proceed toward earning their MS degree. Merging the BS and MS programs allows Columbia students to earn the MS degree in a very flexible and efficient manner.

BARNARD 4+1 PATHWAY APPLICATION
The Barnard 4+1 Pathway is offered to current Barnard College juniors with a GPA of 3.5 or higher to apply to master's programs in Biomedical Engineering, Chemical Engineering, Civil Engineering, Computer Science, Electrical Engineering, Mechanical Engineering, and Industrial Engineering and Operations Research. Students should inquire with Beyond Barnard and plan on attending an introductory information session for the unique 4+1 Pathway they may be interested in pursuing. A maximum of 15 points of credit of graduate-level coursework, completed at Columbia University before the new program is approved and not used toward another degree, may be counted toward the master's degree. Students must enroll in the master’s degree program for at least one semester and must enroll for at least 15 of these points while registered as a matriculating student in a degree program in the Engineering School.

ONE-TERM NONDEGREE STUDENT STATUS
Individuals who meet the eligibility requirements, who are U.S. citizens, U.S. permanent residents, or hold an appropriate visa, and who wish to take courses for enrichment, may secure faculty approval to take up to two graduate-level courses for one term only as a one-term nondegree student. This option is also appropriate for individuals who missed application deadlines. Applications for the one-term nondegree student status are available at the Office of Graduate Student Affairs and must be submitted during the first week of the fall or spring semester.

If a one-term nondegree student subsequently wishes either to continue taking classes the following term or to become a degree candidate, a formal application must be made through the Office of Graduate Student Affairs.

TRANSFER APPLICANTS
Master’s degree students are not eligible for transfer credits.

Students admitted to the doctoral program who have been conferred an appropriate M.S. degree may be awarded two residence units toward their Ph.D., as well as 30 points of advanced standing toward their Ph.D. or Eng.Sc.D., with approval from the academic department and the Office of Graduate Student Affairs.
The 2022–2023 tuition and fees are estimated. Tuition and fees are prescribed by statute and are subject to change at the discretion of the Trustees.

University charges such as tuition and fees are billed in the first Student Account Statement of the term, which is sent out in July and December of each year for the upcoming term. This account is payable and due in full on or before the payment due date announced in the Statement, typically at the end of August or early January before the beginning of the billed term. Any student who does not receive the first Student Account Statement is expected to pay at registration.

If the University does not receive the full amount due for the term on or before the payment due date of the first Statement, a late payment charge of $150 will be assessed. An additional charge of 1.5 percent per billing cycle may be imposed on any amount past due thereafter.

Students with an overdue account balance may be prohibited from registering, changing programs, or obtaining a diploma or transcripts. In the case of persistently delinquent accounts, the University may utilize the services of an attorney and/or collection agent to collect any amount past due thereafter.

Students with an overdue account balance may be prohibited from registering, changing programs, or obtaining a diploma or transcripts. In the case of persistently delinquent accounts, the University may utilize the services of an attorney and/or collection agent to collect any amount past due thereafter.

TUITION
Graduate students enrolled in M.S. and Eng.Sc.D. programs pay $2,362 per credit, except when a special fee is fixed. Graduate tuition for Ph.D. students is $26,008 per Residence Unit. The Residence Unit, full-time registration for one semester rather than for individual courses (whether or not the student is taking courses), provides the basis for tuition charges. Ph.D. students should consult the bulletin for the Graduate School of Arts and Sciences.

COMPREHENSIVE FEE/ MATRICULATION AND FACILITIES
Eng.Sc.D. candidates engaged only in research, and who have completed their twelve (12) credits of Doctoral Research Instruction (see “The Graduate Programs” in this bulletin), are assessed a Comprehensive Fee of $2,490 per term by The Fu Foundation School of Engineering and Applied Science. Ph.D. candidates engaged only in research are assessed $2,490 per term for Matriculation and Facilities by the Graduate School of Arts and Sciences.

MANDATORY FEES
University services and support fee:
- Full-time master’s programs: $601 per term
- Part-time master’s programs: $466 per term
- All other full-time programs: $554 per term
- All other part-time programs: $419 per term
- Health and Related Services fee: $654 per term
- International Services charge: $135 per term (international students only)
- Document fee: $105 (one-time charge)

OTHER FEES
Activities fees for master’s programs:
- First year full-time students (12 or more credits): $400
- Continuing full-time students (12 or more credits): $300
- First year part-time students (less than 12 credits): $200
- Continuing part-time students (less than 12 credits): $150

All full-time and part-time M.S.-Ph.D. track and Ph.D. students shall be charged, per term, a student activities fee of $25.

Application and late fees:
- Application for graduate admission: $85
- Late registration fee:
  - during late registration: $50
  - after late registration: $100

Books and course materials:
- Depends upon course

Laboratory fees: See course listings

IEOR master’s program fee:
- Full-time master’s program: $1,000
- Part-time master’s program: $500
HEALTH INSURANCE
Columbia University offers the Student Medical Insurance Plan, which provides both Basic and Comprehensive levels of coverage. Full-time students are automatically enrolled in the Basic level of the Plan and billed for the insurance premium in addition to the Health Service fee. Visit the Columbia Health website at health.columbia.edu for detailed information about medical insurance coverage options and directions for making confirmation, enrollment, or waiver requests.

PERSONAL EXPENSES
Students should expect to incur miscellaneous personal expenses for such items as food, clothing, linen, laundry, dry cleaning, and so forth. The University advises students to open a local bank account upon arrival in New York City. Since it often takes as long as three weeks for the first deposit to clear, students should plan to cover immediate expenses using either a credit card, traveler’s checks, or cash draft drawn on a local bank. Students are urged not to arrive in New York without sufficient start-up funds.

LABORATORY CHARGES
Students may need to add another $100 to $300 for drafting materials or laboratory fees in certain courses. Each student taking laboratory courses must furnish, at their own expense, the necessary notebooks, blank forms, and similar supplies. In some laboratory courses, a fee is charged to cover expendable materials and equipment maintenance; the amount of the fee is shown with the descriptions in the course listings. Students engaged in special tests, investigations, theses, or research work are required to meet the costs of expendable materials as may be necessary for this work and in accordance with such arrangements as may be made between the student and the department immediately concerned.

DAMAGES
All students will be charged for damage to instruments or apparatus caused by their carelessness. The amount of the charge will be the actual cost of repair, and, if the damage results in total loss of the apparatus, adjustment will be made in the charge for age or condition. To ensure that there may be no question as to the liability for damage, students should note whether the apparatus is in good condition before use and, in case of difficulty, request instruction in its proper operation. Where there is danger of costly damage, an instructor should be requested to inspect the apparatus. Liability for breakage will be decided by the instructor in charge of the course.

When the laboratory work is done by a group, charges for breakage will be divided among the members of the group. The students responsible for any damage will be notified that a charge is being made against them. The amount of the charge will be stated at that time or as soon as it can be determined.

TUITION AND FEE REFUNDS
Students who make a complete withdrawal from a term, including the summer, are assessed a withdrawal fee of $75. Late fees, application fees, withdrawal fees, tuition deposits, special fees, computer fees, special examination fees, and transcript fees are not refundable.

The Health Service Fee, Health Insurance Premium, University facilities fees, and student activity fees are not refundable.

Students who withdraw within the first 60 percent of the academic period are subject to a pro rata refund calculation, which refunds a portion of tuition based on the percentage of the term remaining after the time of withdrawal. This calculation is made from the date the student’s written notice of withdrawal is received by the Office of Graduate Student Affairs.

Percentage Refund for Withdrawal during First Nine Weeks of Term

Prorated for calendars of a different duration, if the entire program is dropped:

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<tr>
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<tr>
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Refund Policy When Dropping Individual Courses
Tuition for courses dropped by the last day of the Change-of-Program period is refunded in full. There is no refund of tuition for individual courses dropped after the last day of the Change-of-Program period. The Change-of-Program period is usually the first two weeks of the fall or spring semesters (please note that the first week of the semester usually begins on a Tuesday).

Please note: The prorated schedule above does not pertain to individual courses dropped (unless your entire schedule consists of only one class). The prorated schedule pertains to withdrawals. Withdrawal is defined as dropping one’s entire program.

For students receiving federal student aid, refunds will be made to the federal aid programs in accordance with Department of Education regulations. Refunds will be credited in the following order:

- Federal Unsubsidized Stafford Loans
- Federal Stafford Loans
- Federal Perkins Loans
- Federal PLUS Loans (when disbursed through the University)
- Federal Pell Grants
- Federal Supplemental Educational Opportunity Grants
- Other Title IV funds

Withdrawing students should be aware that they will not be entitled to any portion of a refund until all Title IV programs are credited and all outstanding charges have been paid.
FINANCING GRADUATE EDUCATION

The academic departments of Columbia Engineering and the Office of Student Financial Planning seek to ensure that all academically qualified students have enough financial support to enable them to work toward their degree. Possible forms of support for tuition, fees, books, and living expenses are: institutional grants, fellowships, teaching and research assistantships, on- or off-campus employment, and student loans. The Office of Student Financial Planning assists students with developing financing plans for completing a degree.

Columbia University graduate funds are administered by two separate branches of the University, and the application materials required by the two branches differ. Institutional grants, fellowships, and teaching and research assistantships are all departmentally-administered funds. Questions regarding these awards should be directed to your academic department. Federal Student Loans (Unsubsidized and Graduate PLUS) and private student loans are administered by the Office of Student Financial Planning.

Questions about loans should be directed to the financial aid office via email at sfp@columbia.edu or phone at 212-854-7040.

Further information can be found at sfs.columbia.edu/sfp-grad-engin.

INSTRUCTIONS FOR FINANCIAL AID APPLICANTS

Deadlines

Apply for financial aid at the same time that you apply for admission. Your admissions application must be received by the December 15 deadline to be eligible for The Fu Foundation School of Engineering and Applied Science departmental funding (institutional grants, fellowships, and teaching and research assistantships). Spring admissions applicants will not be considered for departmental funding.

Incoming applicants and continuing students should complete the FAFSA (studentaid.gov/h/apply-for-aid/fafsa) for fall enrollment.

Guidelines for continuing students are available from departmental advisers in advance of the established deadline. All continuing supported students must preregister for classes during the preregistration period.

GRADUATE SCHOOL DEPARTMENTAL FUNDING

The graduate departments of Columbia Engineering offer an extensive array of funding. Funding decisions, based solely on merit, and contingent upon making satisfactory academic progress, are made by the departments. All applicants for admission and continuing students maintaining satisfactory academic standing will be considered for departmental funds. Applicants should contact their department directly for information. Columbia Engineering prospective and continuing graduate students must complete their FAFSA in order to be considered for all forms of graduate financing (both departmentally-administered and financial aid-administered funds). The application for admission to Columbia Engineering graduate programs is also used to apply for departmental funding. Outside scholarships for which you qualify must be reported to your department and the Office of Student Financial Planning. The School reserves the right to adjust your institutional award if you hold an outside scholarship, fellowship, or other outside funding.

Institutional Grants

Institutional grants are awarded to graduate students on the basis of academic merit. Recipients must maintain satisfactory academic standing.

Fellowships

Fellowships are financial and intellectual awards for academic merit that provide stipends to be used by fellows to further their research. If you are awarded a fellowship, you are expected to devote time to your own work, and you are not required to render any service to the University or donor. You may publish research produced by your fellowship work. As a fellow, you may not engage in remunerative employment without consent of the Dean. Applicants should contact the department directly for information.

Assistantships

Teaching and research assistantships, available to doctoral students in all departments, provide tuition exemption
international students must preregister forms referred to above. Continuing completion of the required financial aid and research assistantships, upon grants, fellowships, and teaching for departmental funding. institution to a Columbia Engineering doctoral December 15 deadline and are admitted to doctoral programs of study by the expenses from their government, a obtain support for their educational degree. Many international students sufficient funding to complete the To secure a visa, international students awards that you will be receiving. Funding for International Students To secure a visa, international students must demonstrate that they have sufficient funding to complete the degree. Many international students obtain support for their educational expenses from their government, a foundation, or a private agency. International students who apply to doctoral programs of study by the December 15 deadline and are admitted to a Columbia Engineering doctoral program are automatically considered for departmental funding (institutional grants, fellowships, and teaching and research assistantships), upon completion of the required financial aid forms referred to above. Continuing international students must preregister for classes during the preregistration period and complete an enrollment status form to be considered for departmental funding. Most private student loan programs are restricted to U.S. citizens and permanent residents. However, international students may be eligible to apply for these domestic loan programs with a creditworthy cosigner who is a citizen or permanent resident in the United States. Depending on the loan program, you may need a valid U.S. Social Security number.

Students who study at Columbia Engineering on temporary visas should fully understand the regulations concerning possible employment under those visas. Before making plans for employment in the United States, international students should consult with the International Students and Scholars Office (ISSO), located at 524 Riverside Drive, Suite 200; 212-854-3587. Its website is isso.columbia.edu.

OTHER FINANCIAL AID—FEDERAL AND PRIVATE PROGRAMS

U.S. citizens and permanent residents enrolled at least half-time in a degree-granting program are eligible to apply for federal student loans. To apply for federal student loans, students should complete the Free Application for Federal Student Aid (FAFSA) using Columbia University’s school code 002707 by May 5 for fall enrollment.

Several private student loan programs are available to both U.S. citizens and international students. These loans require that you have a good credit standing. International students may be eligible for a private loan with a creditworthy U.S. citizen or permanent resident cosigner. Detailed information and application instructions for student loans may be found at the Office of Student Financial Planning website at sfs.columbia.edu/sfp-grad-engin.

Determination of your eligibility for financial aid is based in part on the number of courses for which you register. If you enroll in fewer courses than you initially reported on the loan request form, your loan eligibility may be reduced.

The FAFSA, planned enrollment form, and the loan request form must be completed each academic year, and you must maintain satisfactory academic progress as defined in “The Graduate Programs” section in order to remain eligible for federal student loans.

VETERANS BENEFITS

The U.S. Department of Veterans Affairs, as well as state and local government, offers a number of educational assistance programs for veterans of the U.S. Armed Forces and their dependents. Based on the time and length of service, as well as current status, veterans can be eligible for one or more of these programs. Many benefits are available to advance the education and skills of veterans and service members. Spouses and family members may also be eligible for education and training assistance. Please visit Vets.gov to apply for education benefits.

To qualify for deferred tuition payments, please provide a copy of your Certificate of Eligibility and DD-214 (please note the DD-214 is not required for dependents) to the Columbia Office of Military & Veterans Affairs (OMVA).

• In person to 202 Kent Hall
• Scan and email to veterans@columbia.edu
• Fax to 212-854-2818

For assistance with utilizing your benefits as well as understanding the timeline of payments, please contact a School Certifying Official at 212-854-3161 or veterans@columbia.edu.

For questions related to the status of the VA application or entitlement eligibility, contact the Department of Veterans Affairs at 1-888-442-4551.

Additional resources and veterans news can be found at sfs.columbia.edu/departments/veterans-service.

Veterans Benefits and Transition Act of 2018

In accordance with Title 38 US Code 3679 subsection (e), this school adopts the following additional provisions for any students using U.S. Department of Veterans Affairs (VA) Post 9/11 G.I. Bill® (Ch. 33) or Vocational Rehabilitation and Employment (Ch. 31) benefits, while
payment to the institution is pending from the VA. This school will not:
• Prevent or delay the student's enrollment;
• Assess a late penalty fee to the student;
• Require the student to secure alternative or additional funding;
• Deny the student access to any resources available to other students who have satisfied their tuition and fee bills to the institution, including, but not limited to, access to classes, libraries, or other institutional facilities.

However, to qualify for this provision, such students may be required to:
• Produce the Certificate of Eligibility by the first day of class;
• Provide written request to be certified;
• Provide additional information needed to properly certify the enrollment as described in other institutional policies.

Further information can be found at sfs.columbia.edu/content/information.

EMPLOYMENT
Students on fellowship support must obtain the permission of the Dean before accepting remunerative employment.

Students who study at Columbia Engineering on temporary visas should fully understand the regulations concerning possible employment under those visas. Before making plans for employment in the United States, international students should consult with the International Students and Scholars Office (ISSO) located at 524 Riverside Drive, Suite 200; 212-854-3587. Its website is isso.columbia.edu.

On-Campus Employment
The Graduate Career Placement Center maintains an extensive listing of student employment opportunities. Many resources are available to Columbia engineers and scientists in their job search and career exploration. For more information, visit: career.engineering.columbia.edu

Off-Campus Employment in New York City
One of the nation’s largest urban areas, the city offers a wide variety of opportunities for part-time work. Many students gain significant experience in fields related to their research and study while they meet a portion of their educational expenses.

Gainful Employment Disclosures
Programs: Engineer of Mines and Metallurgical Engineer
• These programs are designed to be completed in 32 weeks.
• These programs will cost $71,998 if completed within the normal time. There may be additional costs for living expenses. These costs were accurate at the time of the posting but may have changed.
• Fewer than 10 students completed this program within the normal time. This number has been withheld to preserve the confidentiality of the students.

For more information about graduation rates, loan repayment rates, and post-enrollment earnings about this institution and other postsecondary institutions, please read further on collegescorecard.ed.gov.


CONTACT INFORMATION
For questions about institutional grants, fellowships, and teaching and research assistantships, contact your academic department.

For questions about on- or off-campus non-need-based employment, contact:

Graduate Career Placement Center
Phone: 646-832-5941
seas-gcp@columbia.edu
career.engineering.columbia.edu.

For questions about student loans, contact:

Office of Student Financial Planning
202 Kent Hall, MC 9205
1140 Amsterdam Avenue
New York, NY 10027
Phone: 212-854-7040
Fax: 212-854-2818
sfp@columbia.edu
sfs.columbia.edu/sfp-grad-engin
Faculty and Administration
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President of the University
Mary C. Boyce, Ph.D.
Provost of the University
Shih-Fu Chang, Ph.D.
Dean
Andrew Laine, D.Sc.
Secretary

FACULTY
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Sunil Agrawal
Professor of Mechanical Engineering
Josh Alman
Assistant Professor of Computer Science
Dimitris Anastassiou
Charles Batchelor Professor of Electrical Engineering
James Anderson
Assistant Professor of Electrical Engineering
Alexandr Andoni
Associate Professor of Computer Science
Treena L. Arinzeh
Professor of Biomedical Engineering
Gerard A. Ateshian
Andrew Walz Professor of Mechanical Engineering and Professor of Biomedical Engineering
Elham Azizi
Assistant Professor of Biomedical Engineering
William E. Bailey
Associate Professor of Materials Science (Henry Krumb School of Mines) and of Applied Physics and Applied Mathematics
Eric Balkanski
Assistant Professor of Industrial Engineering and Operations Research
Scott A. Banta
Professor of Chemical Engineering
Elias Bareinboim
Associate Professor of Computer Science
Katayun Barmak Vaziri
Philips Electronics Professor of Applied Physics and Applied Mathematics
Daniel Bauer
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Peter N. Belhumeur
Professor of Computer Science
Steven M. Bellovin
Perry K. and Vida L. W. Hudson Professor of Computer Science
Keren Bergman
Charles Batchelor Professor of Electrical Engineering
Raimondo Betti
Professor of Civil Engineering and Engineering Mechanics
Daniel Bienstock
Liu Family Professor of Industrial Engineering and Operations Research and Professor of Applied Physics and Applied Mathematics
Simon J. L. Billinge
Professor of Materials Science and of Applied Physics and Applied Mathematics
Kyle J. M. Bishop
Professor of Chemical Engineering
Paul Blaer
Senior Lecturer in Computer Science
David M. Blei
Professor of Computer Science and of Statistics (Arts and Sciences)
Allen H. Boozer
Professor of Applied Physics
Athanasios Bourtsalas
Lecturer in Earth and Environmental Engineering
Christopher Boyce
Assistant Professor of Chemical Engineering
Mary C. Boyce
Morris A. and Alma Schapiro Professor and Professor of Mechanical Engineering
Robert G. Bozic
Lecturer in Chemical Engineering
Michael P. Burke
Associate Professor of Mechanical Engineering
Adam Cannon
Senior Lecturer in Machine Learning (Computer Science)
Agostino Capponi
Associate Professor of Industrial Engineering and Operations Research
Luca Carloni
Professor of Computer Science
Augustin Chaintreau
Associate Professor of Computer Science
Siu-Wai Chan
Professor of Materials Science (Henry Krumb School of Mines) and of Applied Physics and Applied Mathematics
Kartik Chandran
Professor of Earth and Environmental Engineering (Henry Krumb School of Mines)
Julius Chang
Lecturer in Civil Engineering and Engineering Mechanics
Shih-Fu Chang
The Richard Dicker Professor of Telecommunications (Electrical Engineering) and Professor of Computer Science
Jingguang G. Chen
Thayer Lindsley Professor of Engineering (Chemical Engineering)
Xi Chen
Associate Professor of Computer Science
Xi Chen
Professor of Earth and Environmental Engineering (Henry Krumb School of Mines)
Uday Menon  
Associate in Discipline in Industrial Engineering and Operations Research

Nima Mesgarani  
Associate Professor of Electrical Engineering

Vishal Misra  
Professor of Computer Science

Debasis Mitra  
Professor of Electrical Engineering

Vijay Modi  
Professor of Mechanical Engineering

Aaron Moment  
Professor of Professional Practice in Chemical Engineering

Barclay Morrison III  
Professor of Biomedical Engineering

Kristin M. Myers  
Associate Professor of Mechanical Engineering

D. R. Nagaraj  
Professor of Professional Practice in Earth and Environmental Engineering

Arvind Narayananswamy  
Associate Professor of Mechanical Engineering

Gerald A. Navratil  
Thomas Alva Edison Professor of Applied Physics

Shree K. Nayar  
T. C. Chang Professor of Computer Science

Nandan Nerurkar  
Assistant Professor of Biomedical Engineering

Jason Nieh  
Professor of Computer Science

Ismail Cevdet Noyan  
Professor of Materials Science (Henry Krumb School of Mines) and of Applied Physics and Applied Mathematics

Allie C. Obermeyer  
Assistant Professor of Chemical Engineering

Ibrahim S. Odeh  
Senior Lecturer in Civil Engineering and Engineering Mechanics

Elizabeth S. Olson  
Professor of Biomedical Engineering and Auditory Biophysics (in Otolaryngology/Head and Neck Surgery)

Ben O'Shaughnessy  
Professor of Chemical Engineering

John Paisley  
Associate Professor of Electrical Engineering

Thomas Panayotidi  
Lecturer in Civil Engineering and Engineering Mechanics

Christos Papadimitriou  
Donovan Family Professor of Computer Science

Ah-Hyung Alissa Park  
Lenfest Earth Institute Professor in Climate Change (Earth and Environmental Engineering)

Carlos Paz-Soldan  
Associate Professor of Applied Physics and Applied Mathematics

Itsik Pe’er  
Associate Professor of Computer Science

Feniosky Peña-Mora  
Edwin Howard Armstrong Professor of Civil Engineering and Engineering Mechanics and Professor of Earth and Environmental Engineering and of Computer Science

Toniann Pitassi  
Professor of Computer Science

Lorenzo M. Polvani  
Professor of Applied Mathematics and of Earth and Environmental Sciences (Arts and Sciences)

Matthias Preindl  
Associate Professor of Electrical Engineering

Baishakhi Ray  
Assistant Professor of Computer Science

Martin Reiman  
Professor of Industrial Engineering and Operations Research

Kui Ren  
Professor of Applied Physics and Applied Mathematics

Kenneth A. Ross  
Professor of Computer Science

Timothy Roughgarden  
Professor of Computer Science

Dan Rubenstein  
Professor of Computer Science

Amir Sagiv  
Assistant Professor of Applied Physics and Applied Mathematics

Paul Sajda  
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Ansg Salleb-Aouissi  
Senior Lecturer in Computer Science

P. James Schuck  
Associate Professor of Mechanical Engineering

Henning G. Schulzrinne  
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Mingoo Seok  
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Rocco A. Servedio  
Professor of Computer Science

Simha Sethumadhavan  
Professor of Computer Science

Jay Sethuraman  
Professor of Industrial Engineering and Operations Research

Kenneth L. Shepard  
Lau Family Professor of Electrical Engineering and Professor of Biomedical Engineering

Samuel K. Sia  
Professor of Biomedical Engineering

Karl Sigman  
Professor of Industrial Engineering and Operations Research

Mijo Simunovic  
Assistant Professor of Chemical Engineering

Brian Smith  
Assistant Professor of Computer Science
Andrew W. Smyth  
Professor of Civil Engineering and Engineering Mechanics

Adam H. Sobel  
Professor of Applied Physics and Applied Mathematics and of Environmental Sciences (Arts and Sciences)

Ponisseril Somasundaran  
LoVeon Duddleston Krumb Professor of Mineral Engineering (Earth and Environmental Engineering)

Shuran Song  
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Clifford Stein  
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Daniel Steingart  
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Van-Anh Truong  
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Venkat Venkatasubramanian  
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Nakul Verma  
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Sanja Vickovic  
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Xiaodong Wang  
Professor of Electrical Engineering

Michael I. Weinstein  
Professor of Applied Mathematics

Omri Weinstein  
Assistant Professor of Computer Science

Renata Maria Mattosinho Wentzcovitch  
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Alan C. West  
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Harry West  
Professor of Professional Practice in Industrial Engineering and Operations Research

Chris H. Wiggins  
Associate Professor of Applied Mathematics

Jeannette Wing  
Professor of Computer Science

John Wright  
Associate Professor of Electrical Engineering

Eugene Wu  
Associate Professor of Computer Science

Cheng-Shie Wuu  
Professor of Clinical Radiation Oncology, and of Environmental Health Sciences, and of Applied Physics

Bolun Xu  
Assistant Professor of Earth and Environmental Engineering

Junfeng Yang  
Associate Professor of Computer Science

Yuan Yang  
Associate Professor of Applied Physics and Applied Mathematics

Mihalis Yannakakis  
Percy K. and Vida L. W. Hudson Professor of Computer Science

David Da-Wei Yao  
Piyasombatkul Family Professor of Industrial Engineering and Operations Research

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Professor Emeritus of Mechanical Engineering

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Fu Foundation Professor Emeritus of Applied Physics in the Faculty of Engineering and Applied Science

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Paul Diament  
Professor Emeritus of Electrical Engineering

Frank L. DiMaggio  
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Zvi Galil  
Julian Clarence Leu Professor Emeritus of Mathematical Methods and of Computer Science and Dean Emeritus

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Percy K. and Vida L. W. Hudson Professor Emeritus of Chemical Engineering

W. Michael Lai  
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Eugene S. Machlin  
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Professor Emeritus of Electrical Engineering

Van C. Mow  
Stanley Dicker Professor Emeritus of Biomedical Engineering and Professor Emeritus of Orthopedic Engineering (Orthopedic Surgery)

Steven M. Nowick  
Professor of Computer Science and Electrical Engineering

Richard M. Osgood Jr.  
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Enders Robinson  
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Peter Schlosser  
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Michael P. Sheetz  
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Jordan L. Spencer  
Professor Emeritus of Chemical Engineering

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Professor Emeritus of Engineering Science

Rene B. Testa  
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Nickolas J. Themelis  
Professor Emeritus of Earth and Environmental Engineering

Stephen H. Unger  
Professor Emeritus of Computer Science and of Electrical Engineering

Rimas Vaicaitis  
Renwick Professor Emeritus of Civil Engineering

Henryk Wozniakowski  
Professor Emeritus of Computer Science

Edward S. Yang  
Professor Emeritus of Electrical Engineering

Tuncel M. Yegulalp  
Professor Emeritus of Mining (Earth and Environmental Engineering, Henry Krumb School of Mines)

Yechiam Yemini  
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Assistant Director, Columbia Video Network

William Yandolino
Executive Director of Finance and Operations

Sara Yllescas
Career Placement Officer, Computer Science

Marina Zamalin
Executive Director of Online Learning

Yiwei Zhang
Assistant Director of International Graduate Student Services
Academic Departments and Programs
This section contains a description of the curriculum of each department in the School, along with information regarding undergraduate and graduate degree requirements, elective courses, and suggestions about courses and programs in related fields. All courses are listed, whether or not they are being offered during the current year; if a course is not being given, that is indicated. Included as well are courses cross-listed with other departments and undergraduate divisions within the University.

**DESIGNATORS**
Each course is preceded by a four-letter designator, which indicates the department or departments presenting the course.

<table>
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<tr>
<th>Course Designator</th>
<th>Department Subject</th>
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<tbody>
<tr>
<td>AHIS</td>
<td>Art History</td>
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<tr>
<td>AMCS</td>
<td>Applied Math and Computer Science</td>
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<td>AMST</td>
<td>American Studies</td>
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<td>Anthropology</td>
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<td>Applied Physics and Applied Math</td>
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<td>APBM</td>
<td>Applied Physics and Biomedical Engineering</td>
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<td>APCH</td>
<td>Applied Physics and Chemical Engineering</td>
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<td>APMA</td>
<td>Applied Mathematics</td>
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<td>APPH</td>
<td>Applied Physics</td>
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<td>ASCM</td>
<td>Asian Civilization: Middle East</td>
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<td>Astronomy</td>
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<td>Biomedical Engineering, Electrical Engineering, and Biology</td>
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<td>BMME</td>
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<td>BUSI</td>
<td>Business</td>
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<td>CBMF</td>
<td>Computer Science, Biomedical Engineering and Medical Informatics</td>
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<td>CEOR</td>
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<td>Chemical Engineering and Biomedical Engineering</td>
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<td>CHCB</td>
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<td>Dance</td>
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<td>DROM</td>
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<td>EEHS</td>
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<td>EESC</td>
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<td>Engineering Mechanics and Mechanical Engineering</td>
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<td>FREN</td>
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<td>GRAP</td>
<td>Graphics</td>
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<td>History</td>
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<td>History and Applied Mathematics</td>
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<td>Industrial Engineering and Mechanical Engineering</td>
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<td>INAF</td>
<td>International Affairs</td>
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<td>INTA</td>
<td>Earth and Environmental Engineering, Civil Engineering, and International and Public Affairs</td>
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<td>Management Science and Industrial Engineering and Operations Research</td>
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<td>Statistics and Industrial Engineering and Operations Research</td>
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<td>Urban Studies</td>
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<tr>
<td>VIAR</td>
<td>Visual Arts</td>
</tr>
</tbody>
</table>

**How Courses Are Numbered**

The course number that follows each designator consists of one or two capital letters followed by four digits. The capital letter indicates the University division or affiliate offering the course:

- **B**: Business
- **E**: Engineering and Applied Science
- **P**: Mailman School of Public Health
- **S**: Summer Session
- **U**: International and Public Affairs
- **W**: Interfaculty course
- **Z**: American Language Program

**Arts and Sciences**

- CC: Columbia College
- UN: Undergraduate
- GU: Undergraduate, Graduate
- GR: Graduate Only

The first digit indicates the level of the course, as follows:

- **0**: Course that cannot be credited toward any degree
- **1**: Undergraduate course
- **2**: Undergraduate course, intermediate
- **3**: Undergraduate course, advanced
- **4**: Graduate course that is open to qualified undergraduates
- **6**: Graduate course
- **8**: Graduate course, advanced
- **9**: Graduate research course or seminar

An x following the course number means that the course meets in the fall semester; y indicates the spring semester.

**Directory of Classes**

Room assignments, days and hours, and course changes for all courses are available online at columbia.edu/cu/bulletin/uwb.

The School reserves the right to withdraw or modify the courses of instruction or to change the instructors at any time.
Applied Physics and Applied Mathematics

The Department of Applied Physics and Applied Mathematics includes undergraduate and graduate studies in the fields of applied physics, applied mathematics, and materials science and engineering. The graduate program in applied physics includes plasma physics and controlled fusion; solid-state physics; optical and laser physics and medical physics. The graduate program in applied mathematics includes research in applied analysis, data science, and atmospheric, oceanic, and earth physics. The graduate programs in materials science and engineering are described on pages 181–183.

Current Research Activities in Applied Physics and Applied Mathematics

Applied Physics.

Plasma physics and fusion energy.

In experimental plasma physics, research is being conducted on (1) equilibrium, stability, and transport in fusion plasmas: high-beta tokamaks, spherical tokamaks, and levitated dipoles; (2) magnetospheric physics: trapped particle instabilities and stochastic particle motion; (3) confinement of toroidal nonneutral plasmas; (4) plasma source operation and heating techniques; and (5) the development of new plasma measurement techniques. The results from our fusion science experiments are used as a basis for collaboration with large national and international experiments. For example, methods of active feedback control of plasma instability developed at Columbia University are guiding research on NSTX at the Princeton Plasma Physics Laboratory, on the DIII-D tokamak at General Atomics, and for the design of the next-generation tokamak at General Atomics.
burning plasma experiment, ITER. In theoretical plasma physics, research is conducted in the theory of plasma equilibrium and stability, active control of MHD instabilities, the kinetic theory of turbulence and transport, and the development of techniques based on the theory of general coordinates and dynamical systems. The work is applied to magnetic fusion, nonneutral and space plasmas.

**Optical and laser physics.** Active areas of research include inelastic light scattering in nanomaterials, optical diagnostics of film processing, flat optics, metasurfaces, nonlinear optics, ultrafast optoelectronics, photonic switching, optical physics of surfaces, laser-induced crystallization, and photon integrated circuits.

**Solid-state physics.** Research in solid-state physics covers nanoscience and nanoparticles, electronic transport and inelastic light scattering in low-dimensional correlated electron systems, heterostructure physics and applications, grain boundaries and interfaces, nucleation in thin films, molecular electronics, nanostructure analysis, and electronic structure calculations.

Applied physics is part of the Columbia Quantum Initiative. Research opportunities also exist within the Columbia Nano Initiative (CNI), including the NSF Materials Research Science and Engineering Center, which focuses on low dimensional materials.

**Applied mathematics.** Current research encompasses analytical and numerical analysis of deterministic and stochastic partial differential equations, large-scale scientific computation, fluid dynamics, dynamical systems and chaos, inverse problems, algorithms for data and learning, as well as applications to various fields of physical and biological sciences. The applications to physical science include quantum and condensed-matter physics, materials science, electromagnetics, optics, photonics, plasma physics, medical imaging, and the earth sciences, notably atmospheric, oceanic, and climate science, and solid earth geophysics (see below). Other applications include machine learning and biophysical modeling, e.g., collaborations with Columbia’s Data Science Institute (DSI), the Department of Systems Biology, and the Department of Statistics. Extensive collaborations exist with national climate research centers (the Geophysical Fluid Dynamics Laboratory and the National Center for Atmospheric Research) and with national laboratories of the U.S. Department of Energy, custodians of the nation’s most powerful supercomputers.

**Atmospheric, oceanic, and earth physics.** Current research focuses on the dynamics of the atmosphere and the ocean, climate modeling, cloud physics, radiation transfer, remote sensing, geophysical/geological fluid dynamics, and geochemistry. The department engages in ongoing research with the NASA Goddard Institute for Space Studies and the Lamont-Doherty Earth Observatory. Seven faculty members share appointments with the Department of Earth and Environmental Sciences.

In addition to the faculty and graduate students, many others participate in these projects, including full-time research faculty, faculty and students from other departments, and visiting scientists.

**Laboratory and Computational Facilities in Applied Physics and Applied Mathematics**

The Plasma Physics Laboratory, founded in 1961, is one of the leading university laboratories for the study of plasma physics in the United States. There are four experimental facilities. The Columbia High-Beta Tokamak (HBT-EP) supports the national program to develop controlled fusion energy. It utilizes high voltage, pulsed power systems, and laser and magnetic diagnostics to study the properties of high-beta plasmas and the use of feedback stabilization to increase the achievable beta. A collaborative program with the Princeton Plasma Physics Laboratory and the DIII-D tokamak group at General Atomics is studying the properties of high-beta plasmas in order to maximize fusion power production in these large, neutral beam-heated tokamaks and spherical tori. The stellarator known as Columbia Nonneutral Torus (CNT) conducts research on the magnetohydrodynamic stability, microwave heating, and microwave diagnostics of neutral stellarator plasmas. Two smaller devices investigate, respectively, an innovative tokamak-stellarator hybrid plasma confinement concept and the use of toroidal electron-heated plasmas as sources of ions for accelerators. The Columbia Linear Machine (CLM) is a continuously operating, linear mirror device for the study of collisionless plasma instabilities, plasma, transport, and feedback stabilization. Columbia’s Collisionless Terrella Experiment investigates plasma transport in magnetospheric geometry and the generation of strong plasma flow from nonlinear electrostatic potentials.

Experimental research in solid-state physics and laser physics is conducted within the department and also in association with the Columbia Nano Initiative. Facilities include laser processing and spectroscopic apparatus, ultrahigh vacuum chambers for surface analysis, picosecond and femtosecond lasers, and a clean room that includes photo-lithography and thin film fabrication systems. Within this field, the Laser Diagnostics and Solid State Physics Laboratory conducts studies in laser spectroscopy of nanomaterials and semiconductor thin films, and laser diagnostics of thin film processing. The Laser Lab focuses on the study of laser surface chemical processing and new semiconductor structures. Research is also conducted in the shared characterization laboratories and clean room operated by CNI.

The department maintains an extensive network of computing clusters and desktop computers. The research of the Plasma Lab is supported by a dedicated data acquisition/data analysis system. The department has a leadership role in development and support of Columbia Shared Computing resources and has access to multiple HPC clusters. Researchers in the department are additionally using supercomputing facilities at the National Center for Atmospheric Research; the San Diego Supercomputing Center; the National Energy Research
Supercomputer Center in Berkeley, California; the National Leadership Class Facility at Oak Ridge, Tennessee; various allocations via XSEDE; and others. The Amazon Elastic Compute Cloud (EC2) is also utilized to supplement computing resources in times of high demand.

**Current Research Activities and Laboratory Facilities in Materials Science and Engineering**

See pages 177–178.

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### UNDERGRADUATE PROGRAMS

The Department of Applied Physics and Applied Mathematics offers three undergraduate programs: applied physics, applied mathematics, and materials science. The materials science program is described on pages 178–181.

The applied physics and applied mathematics programs provide an excellent preparation for graduate study or for careers in which mathematical and technical sophistication are important. Using the large number of electives in these programs, students can tailor their programs to fit their personal and career interests. By focusing their technical electives, students can obtain a strong base of knowledge in a specialized area. In addition to formal minors, some areas of specialization that are available are described on pages 53–54. All technical electives are normally at the 3000 level or above.

### UNDERGRADUATE PROGRAM IN APPLIED PHYSICS

The applied physics program stresses the basic physics that underlies most developments in engineering and the mathematical tools that are important to both physicists and engineers. Since the advances in most branches of technology

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<table>
<thead>
<tr>
<th>MATHEMATICS¹</th>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
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<tr>
<td></td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0) either semester</td>
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<td>UN2601 (3.5)</td>
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<tr>
<td>UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
<td>Lab UN1494 (3)</td>
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<td>ENGI E1102 (4) (3)¹</td>
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<td>ENGI E1006 (3)¹</td>
<td>any semester</td>
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<th>COMPUTER SCIENCE</th>
<th>ENGI E1006 (3)¹ any semester</th>
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<table>
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<th>PHYSICAL EDUCATION</th>
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<th>UN1002 (1)</th>
<th>ENGI E1102 (4) (3)¹</th>
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<thead>
<tr>
<th>THE ART OF ENGINEERING</th>
<th>ENGI E1102 (4) either semester</th>
</tr>
</thead>
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¹ Students with advanced standing may start the calculus sequence at a higher level (see page 12 for placement), in which case students are suggested to add linear algebra in the first two years.

² Applied physics majors should satisfy their ODE requirement with the Mathematics Department (ordinarily MATH UN2030). Students who take APMA E2101 prior to declaring their major in applied physics may use this course to satisfy their ODE requirement with the permission of the faculty adviser.

³ With permission of faculty adviser, students demonstrating familiarity with computational mathematics using Python may waive course requirement and use 3 credits for another technical course.
lead to rapid changes in state-of-the-art techniques, the applied physics program provides the student with a broad base of fundamental science and mathematics while retaining the opportunity for specialization through technical electives.

The applied physics curriculum offers students the skills, experience, and preparation necessary for several career options, including opportunities to minor in economics and to take business-related courses. In recent years, applied physics graduates have entered graduate programs in many areas of applied physics or physics, enrolled in medical school, or been employed in various technical or financial areas immediately after receiving the B.S. degree.

Opportunities for undergraduate research exist in the many research programs in applied physics. These include fusion and space plasma physics, optical and laser physics, and condensed matter physics. Undergraduate students can receive course credit for research or an independent project with a faculty member. Opportunities also exist for undergraduate students in the applied physics program to participate in this research through part-time employment during the academic year and full-time employment during the summer, either at Columbia or as part of the NSF REU program nationwide. Practical research experience is a valuable supplement to the formal course of instruction. Applied physics students participate in an informal undergraduate seminar to study current and practical problems in applied physics and obtain hands-on experience in at least two advanced laboratory courses.

Majors are introduced to two areas of application of applied physics (AP) by a course in each of two areas. Approved areas and courses are:

- **DYNAMICAL SYSTEMS:**
  - APMA E4101 or PHYS GU4003

- **OPTICAL OR LASER PHYSICS:**
  - APPH E4110 or E4112

- **NUCLEAR SCIENCE:**
  - APPH E4010

- **PLASMA PHYSICS:**
  - APPH E4301

- **PHYSICS OF FLUIDS:**
  - APPH E4200

- **SOLID-STATE/CONDENSED MATTER PHYSICS:**
  - PHYS GU4018

- **BIOPHYSICAL MODELING:**
  - APMA E4400

In addition to these courses, courses listed in the Specialty Areas in Applied Physics can be used to satisfy this requirement with preapproval of the applied physics adviser.

All students must take 30 points of electives in the third and fourth years, of which 17 points must be technical courses approved by the adviser. The 17 points include 2 points of an advanced laboratory in addition to APPH E4018. Technical electives must be at the 3000 level or above unless prior approval is obtained.

### UNDERGRADUATE PROGRAM IN APPLIED MATHEMATICS

The applied mathematics program is flexible and intensive. A student must take the required courses listed below, or prove equivalent standing, and then may elect the other courses from mathematics, computer science, physics, earth and environmental sciences, biophysics, economics, business and finance, or other application fields.
Each student tailors their own program in close collaboration with an adviser and should confer with their adviser on a regular basis to make sure they are on track for graduation. In particular, all required courses listed in the table must be taken to graduate, however, the specific sequence in which they are taken may depend somewhat on the student’s area of specialization. In general, each student should always check with their adviser. They must also register for the applied mathematics seminar during both the junior and senior years. During the junior year, the student attends the seminar lectures for 0 points; during the senior year, they attend the seminar lectures as well as tutorial problem sessions for 3 or 4 points.

While it is common for students in the program to go on to graduate school, many graduating seniors will find employment directly in industry, government, education, or other fields. Of the 27 points of elective content in the third and fourth years, at least 15 points of technical courses approved by the adviser must be taken. The remaining points of electives are intended primarily as an opportunity to complete the absolutely mandatory four-year, 27-point nontechnical requirement for the B.S. degree, but if this 27-point nontechnical requirement has been met already, then any type of coursework can satisfy these elective points.

Transfers into the applied mathematics program from other majors require a GPA of 3.0 or above, and the approval of the applied mathematics program chair.

### UNDERGRADUATE DOUBLE MAJOR IN APPLIED PHYSICS AND APPLIED MATHEMATICS

Students satisfy all requirements for both majors, except for the seminar requirements. They are required to take both senior seminars, APMA E4903 and APPH E4903 (taking one in the junior year and one in the senior year, due to
### APPLIED MATHEMATICS: THIRD AND FOURTH YEARS

<table>
<thead>
<tr>
<th></th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
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<tbody>
<tr>
<td>REQUIRED COURSES</td>
<td>APMA E3101 (3)(^1) Linear algebra (Applied math, I)</td>
<td>APMA E3102 (3)(^1) Partial differential equations (Applied math, II)</td>
<td>MATH GU4061 (3)(^1) Modern analysis</td>
<td>APMA E3900 (3)(^3) Research Courses designated MATH, APMA, or STAT (3)</td>
</tr>
<tr>
<td></td>
<td>APMA E4204 (3)(^1) Complex variables</td>
<td>APMA E4101 (3)(^1) Introduction to dynamical systems (Applied math, III)</td>
<td>APMA E4903 (3 or 4) Seminar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>APMA E4901 (0) Seminar</td>
<td>Course from Group A(^2)</td>
<td></td>
<td></td>
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<td>3 points</td>
<td>3 points</td>
<td>6 points</td>
</tr>
<tr>
<td>NONTECH</td>
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<td>3 points</td>
<td>3 points</td>
<td>3 points</td>
</tr>
<tr>
<td>TOTAL POINTS</td>
<td>15</td>
<td>15</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

1 MATH UN2010 or COMS W3561 may be substituted for APMA E3101; MATH UN3028 may be substituted for APMA E3102; MATH UN3007 may be substituted for APMA E4204. MATH UN2500 may be substituted for MATH GU4061.


3 With an adviser’s permission, an approved technical elective may be substituted.

4 Any course in science, math, or engineering at the 3000 level or above qualifies as a technical elective, except for required or elective courses in the minor in entrepreneurship and innovation which do not count as technical electives unless authorized by an adviser. Elective courses may be chosen from other departments in SEAS and Arts and Sciences, e.g., the Departments of Mechanical Engineering, Electrical Engineering, Mathematics, and Statistics.

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To timing conflicts), but not the junior seminars, APMA E4901 and APPH E4901. A single foundational course may be used to fulfill a requirement in both majors. Students must maintain a GPA at or above 3.75, and must graduate with at least 143 points, 15 above the regular 128-point requirement. These extra 15 points should be technical electives appropriate for one or both majors.

To apply, a student first obtains the approval of both the general undergraduate Applied Physics adviser and the general undergraduate Applied Mathematics adviser, and then the approval of the Dean.

### SPECIALTY AREAS IN APAM

Both applied physics and applied mathematics students can focus their technical electives and develop a strong base of knowledge in a specialty area. There is no requirement to focus electives, so students may take as many or as few of the recommended courses in a specialty area as is appropriate to their schedules and interests. Some specialties are given below, but this is not an exclusive list, and others can be worked out in coordination with the student’s adviser. The courses that are often taken, or in some cases need to be taken, in the junior year are denoted with a “J.”

#### Technical Electives

- **Applications of Physics**
  
  Courses that will give a student a broad background in applications of physics:
  
  **ELEN E3000x:** Circuits, systems, and electronics (J)
  
  **MSAE E3010x:** Introduction to materials science, I
  
  **APPH E4010x:** Intro to nuclear science
  
  **PHYS GU4018y:** Solid state physics
  
  **APMA E4101x:** Intro to dynamical systems
  
  **APPH E4110y:** Modern optics
  
  **APPH E4112x:** Laser physics
  
  **APPH E4200x:** Physics of fluids
  
  **APPH E4301y:** Intro to plasma physics

- **Earth and Atmospheric Sciences**
  
  The earth sciences provide a wide range of problems of interest to physicists and mathematicians ranging from the dynamics of Earth’s climate to earthquake physics to dynamics of Earth’s deep interior. The Lamont-Doherty Earth Observatory, which is part of Columbia University, provides enormous resources for students interested in this area.

**ATMOSPHERE, OCEANS, AND CLIMATE**

- **APAM E3109:** Climate physics
- **EESC GU4008:** Intro to atmospheric science
- **APPH E4200x:** Physics of fluids
- **APPH E4210x:** Geophysical fluid dynamics
- **EESC GU4925:** Principles of physical oceanography
• **Numerical methods for partial differential equations**

  - **APMA E4101x**: Intro to dynamical systems
  - **APMA E4300x**: Methods in computational mathematics
  - **APMA E4302x**: Methods in computational biology

  **• Fundamental Mathematics in Applied Physics**

  This specialization is intended for students who desire a more solid foundation in the mathematical methods and underlying theory. For example, this specialization could be followed by students with an interest in graduate work in applied mathematics.

  - **MATH UN3386x**: Differential geometry
  - **APMA E4101x**: Intro to dynamical systems
  - **APMA E4150x**: Applied functional analysis
  - **MATH GU4032x**: Modern analysis, II
  - **STAT GU4001x, y**: Intro to probability and mathematical statistics (J)

  **• Quantitative Biology**

  Traditionally biology was considered a descriptive science in contrast to the quantitative sciences that are based on mathematics, such as physics. This view no longer coincides with reality. Researchers from biology as well as from the physical sciences, applied mathematics, and computer science are rapidly building a quantitative base of biological knowledge. Students can acquire a strong base of knowledge in quantitative biology, both biophysics and computational biology, while completing the applied physics or applied mathematics programs.

  - **BIOL UN3005y**: Intro biology, I and II
  - **APPH E3400y**: Physics of the human body
  - **APMA E4400y**: Intro to biophysical modeling

  **• Scientific Computation and Computer Science**

  Advanced computation has become a core tool in science, engineering, and mathematics and provides challenges for both physicists and mathematicians. Courses that build on both practical and theoretical aspects of computing and computation include:

  - **MATH UN3020x**: Number theory and cryptography (J)
  - **COMS W3117x,y**: Data structures and algorithms (J) (or COMS W3137y: Honors data structures and algorithms) (J)
  - **COMS W3157x,y**: Advanced programming (J)
  - **COMS W3203x,y**: Discrete mathematics: intro to combinatorics and graph theory (J)
  - **COMS W4203y**: Graph theory
  - **APMA E4300x**: Intro to numerical methods
  - **APMA E4301y**: Numerical methods for partial differential equations
  - **APMA E4302x**: Methods in computational science
  - **COMS W4701x,y**: Artificial intelligence
  - **COMS W4771y**: Machine learning

  **• Solid-State Physics**

  Much of modern technology is based on solid-state physics, the study of solids and liquids. Courses that will build a strong base for a career in this area are:

  - **PHYS UN3083y**: Electronics laboratory (J)
  - **MASE E3110x**: Introduction to materials science (J)
  - **ELEN E3106x**: Solid state devices and materials (J)
  - **MASE E4100x**: Crystallography
  - **PHYS GU4108y**: Solid state physics
  - **MASE E4206x**: Electronic and magnetic properties of solids

**UNDERGRADUATE PROGRAM IN MATERIALS SCIENCE**

See page 178.

**GRADUATE PROGRAMS**

Financial aid is available for students pursuing a doctorate, fellowships,
scholarships, teaching assistantships, and graduate research assistantships are awarded on a competitive basis. The Aptitude Test of the Graduate Record Examination is required of candidates for admission to the department and for financial aid; the Advanced Tests are recommended.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–E6004 and should consult their program for specific PDL requirements.

Ethics training is required of all students pursuing a doctorate.

**M.S. Program in Applied Physics**

This 30-point program of study leading to the degree of Master of Science, while emphasizing continued work in basic physics, permits many options in several applied physics specialties. The program may be considered simply as additional education in areas beyond the bachelor’s level, or as preparatory to doctoral studies in the applied physics fields of plasma physics, laser physics, or solid-state physics. Specific course requirements for the master’s degree are determined in consultation with the program adviser, but must include four of the six core courses listed below.

The core courses provide a student with a solid foundation in the fundamentals of applied physics, but with the approval of the faculty adviser, other graduate-level courses with APPH designators not listed below may also count as core courses.

- **APPH E4100**: Quantum physics of matter
- **APPH E4110**: Modern optics
- **APPH E4112**: Laser physics
- **APPH E4200**: Physics of fluids
- **APPH E4300**: Applied electrodynamics
- **APPH E4301**: Introduction to plasma physics

**M.S. Program in Applied Mathematics**

This 30-point program leads to a Master of Science degree. Students must complete five core courses and five electives. All degree requirements must be completed within five years. A candidate is required to maintain at least a 2.5 grade point average. If a student admitted to the Applied Mathematics M.S. only program is interested in the Ph.D. program, the student must reapply for admission. The core courses provide a student with a foundation in the fundamentals of applied mathematics and contribute 15 points of graduate credit toward the degree. Students must complete five of the following nine courses:

- **APMA E4101**: Intro to dynamical systems
- **APMA E4150**: Applied functional analysis
- **APMA E4200**: Partial differential equations
- **APMA E4204**: Functions of a complex variable
- **APMA E4300**: Intro to numerical methods
- **APMA E4301**: Numerical methods for partial differential equations
- **APMA E6301**: Analytic methods for partial differential equations
- **APMA E6302**: Numerical analysis for partial differential equations

Students must also take a required Research Seminar course, APMA E6100 x or y.

A student must select five elective courses from those listed below (or any of those not used to satisfy the core requirements from the list above) for a total of 15 points of graduate credit. Additional courses not listed below can be applied toward the elective requirements, subject to the approval of the faculty adviser*.

*Courses from the Department of Economics, Business School, School of International and Public Affairs, or quantitative courses offered by the School of Professional Studies may not be counted as electives toward the degree.
Computer science elective courses include:

- **CSOR W4231:** Analysis of algorithms, I
- **COMS W4236:** Intro to computational complexity
- **COMS W4241:** Numerical algorithms and complexity
- **COMS W4252:** Computational learning theory

Industrial engineering/operations research elective courses include**:

- **IEOR E4003:** Industrial economics
- **IEOR E4004:** Intro to operations research: deterministic models
- **IEOR E4007:** Optimization: models and methods
- **IEOR E4106:** Stochastic models
- **STAT GU4001:** Intro to probability and statistics
- **IEOR E4403:** Advanced engineering and corporate economics
- **IEOR E4407:** Game theoretic models of operations
- **STAT GU4606:** Elementary stochastic processes
- **IEOR E4700:** Intro to financial engineering

**Please check IEOR website for registration procedures required of non-IEOR students.

Other elective courses may be chosen from other departments in SEAS and Arts and Sciences, e.g., the Departments of Mechanical Engineering, Electrical Engineering, Mathematics, and Statistics.

**M.S. Program in Materials Science and Engineering**

See page 181.

**M.S. Program in Medical Physics**

This CAMPEP-approved 36-point program in medical physics leads to the M.S. degree. It is administered by faculty from the School of Engineering and Applied Science in collaboration with faculty from the College of Physicians and Surgeons and the Mailman School of Public Health. It provides preparation toward certification by the American Board of Radiology. The program consists of a core curriculum of medical and nuclear physics courses, anatomy, lab, seminar, a tutorial, one elective, and two practicums. Specific course requirements are APPH E4010, E4330, E4710, E4500, E4550, E4600, E6319, E6330, E6335, and APBM E4650. Approved electives include APPH E4711, APPH E6336, APAM E6650, and a third practicum. Up to 6 points of this 36-point program may be waived based on prior equivalent academic work. A student who enters the 36-point M.S. Program, in Medical Physics, having satisfactorily completed, prior to beginning the Program, a course determined by the faculty to be equivalent in content to a required course within the Program, may be considered to have satisfied that content requirement, may be allowed to have that requirement waived, and may be permitted to graduate from the M.S. Program in Medical Physics with fewer than 36 points, but not fewer than the 30-point minimum required by the School of Engineering and Applied Science. Evaluation of prior coursework may include review of syllabi, comparison of textbooks, consultation with instructors, and/or written or oral examination administered by Program faculty. A passing grade on a comprehensive examination is required for graduation. This examination, on subjects covered in the curriculum, is taken after two terms of study.

**Certification of Professional Achievement in Medical Physics**

This graduate program of instruction leads to the Certification of Professional Achievement and requires satisfactory completion of six of the following courses:

- **APPH E4330:** Radiobiology
- **APPH E4500:** Health physics
- **APPH E4600:** Dosimetry
- **APBM E4650:** Anatomy for physicists and engineers
- **APPH E6319:** Clinical nuclear medicine physics or APPH E6330: Diagnostic radiology physics
- **APPH E6335:** Radiation therapy physics or APPH E6336: Advanced topics in radiation therapy

This is a part-time nondegree program. Students are admitted to the department as certificate-track students.

**PH.D. AND ENG.SC.D. PROGRAMS**

After completing the M.S. program, doctoral students specialize in one area of their programs. Some specializations have specific course requirements for the doctorate; elective courses are determined in consultation with the program adviser. Successful completion of an approved 30-point program of study is required in addition to successful completion of a written qualifying examination taken after two semesters of graduate study. An oral examination, taken within one year after the written qualifying examination, and a thesis proposal examination, taken within two years after the written qualifying examination, are required of all doctoral candidates, as is training in research and professional ethics in the first two years of the doctoral program.

**Applied Mathematics**

Applied mathematics deals with mathematical concepts and techniques used in various fields of science and engineering. Historically, mathematics was first applied with great success in astronomy and mechanics. Then it developed into a main tool for physics, other physical science, and engineering. It is now becoming important in the biological, geological, economics, business, etc. With the coming of age of the computer, applied mathematics transcended its traditional style and now assumes an even greater importance and a new vitality.

Compared with the pure mathematician, the applied mathematician is more interested in problems coming from other fields. Compared with the engineer and the physical scientist, the applied mathematician is more concerned with the formulation of problems and the nature of solutions. Compared with the computer scientist, the applied mathematician is more concerned with the accuracy of approximations and the interpretation of results. Needless to say, even in this age of specialization, the work of mathematicians, scientists, and engineers frequently overlaps. Applied mathematics, by its very nature, has occupied a central position in this interplay and has remained a field of fascination and excitement for active minds.

The Applied Analysis specialty includes research on analytical and numerical partial differential equations; mathematical foundations of data analytics, uncertainty quantification, stochastic analysis; large-scale scientific computation; fluid dynamics and continuum mechanics; dynamical systems and chaos; and applications to various fields of data and physical and life sciences.

The Atmospheric, Oceanic, and Earth Physics specialty includes research on dynamics of the atmosphere and the ocean; climate modeling; cloud physics; radiation transfer; remote sensing; geophysical/geological fluid dynamics; and geochemistry.
Courses:
APMA E4101: Intro to dynamical systems
APMA E4105: Applied functional analysis
APMA E4200: Partial differential equations
APMA E4204: Functions of a complex variable
APMA E4300: Intro to numerical methods
APMA E4301: Numerical methods for partial differential equations
APMA E4302: Intro to computational science
APMA E4400: Intro to biophysical modeling
APMA E6301: Analytic methods for partial differential equations
APMA E6302: Numerical analysis for partial differential equations

Related courses of specialization:
APMA E6901: Special topics in applied mathematics
APMA E8308: Asymptotic methods in applied mathematics
APPH E4210: Geophysical fluid dynamics
APPH E9815: Geophysical fluid dynamics seminar
COMS E4205: Combinatorial theory
COMS E4241: Numerical algorithms and complexity
EESC GU4008: Introduction to atmospheric science
PHYS GU4019: Mathematical methods in physics
MATH GU4032: Fourier analysis

Materials Science and Engineering Program
See page 181.

Applied Physics
This doctoral program has three specialties. APPH E4018 Applied physics laboratory is required for each of the three specialties in the first year of the doctoral program, in addition to any specific courses required of each specialty.

Plasma Physics
This graduate specialty is designed to emphasize preparation for professional careers in plasma research, controlled fusion, and space research. This includes basic training in relevant areas of applied physics, with emphasis on plasma physics and related areas leading to extensive experimental and theoretical research in the Columbia University Plasma Physics Laboratory. Specific course requirements for the plasma physics doctoral program are APPH E4018, E4200, E4300, E6101, E6102, and E9142 or E9143, or equivalents taken at another university.

Optical and Laser Physics
This graduate specialty involves a basic training in relevant areas of applied physics, with emphasis in quantum mechanics, quantum electronics, and related areas of specialization. Some active areas of research in which the student may concentrate are laser modification of surfaces, optical diagnostics of film processing, inelastic light scattering in nanomaterials, nonlinear optics, ultrafast optoelectronics photonic switching, optical physics of surfaces, and photon integrated circuits. Specific course requirements for the optical and laser physics doctoral specialization are set with the academic adviser.

Solid-State Physics
This graduate specialty encompasses the study of the electrical, optical, magnetic, thermal, high-pressure, and ultrafast dynamical properties of solids, with an aim to understanding them in terms of the atomic and electronic structure. The field emphasizes the formation, processing, and properties of thin films, low-dimensional structures—such as one- and two-dimensional electron gases, nanocrystals, surfaces of electronic and optoelectronic interest, and molecules. Facilities include a microelectronics laboratory, high-pressure diamond anvil cells, a molecular beam epitaxy machine, ultrahigh vacuum systems, lasers, equipment for the study of optical properties and transport on the nanoscale, and the instruments in the shared facilities overseen by the Columbia Nano Initiative (CNI). There are also significant resources for electrical and optical experimentation at low temperatures and high magnetic fields. Specific course requirements for the solid-state physics doctoral specialization are set with the academic adviser, in consultation with the Committee on Materials Science and Engineering/Solid-State Science and Engineering.

COURSES IN APPLIED PHYSICS

APPH E3100y Introduction to quantum mechanics
3 pts. Lect: 3. Professor Herman.
Prerequisite(s): PHYS UN1403 or equivalent, and differential and integral calculus. Corequisite(s): APMA E3101 or equivalent. Basic concepts and assumptions of quantum mechanics, Schrodinger’s equation, solutions for one-dimensional problems, including square wells, barriers, and the harmonic oscillator, introduction to the hydrogen atom, atomic physics and X-rays, electron spin.

APPH E3200x Mechanics: fundamentals and applications
3 pts. Lect: 3. Professor Mauel.
Prerequisite(s): PHYS UN1402, MATH UN2030, or equivalent. Basic non-Euclidean coordinate systems, Newtonian mechanics, oscillations, Green’s functions, Newtonian gravitation, Lagrangian mechanics, central force motion, two-body collisions, noninertial reference frames, rigid body dynamics. Applications, including GPS and feedback control systems, are emphasized throughout.

APPH E3300y Applied electromagnetism
3 pts. Lect: 3. Members of the faculty.
Corequisite(s): APMA E3102. Vector analysis, electrostatic fields, Laplace’s equation, multipole expansions, electric fields in matter: dielectrics, magnetostatic fields, magnetic materials, and superconductors. Applications of electromagnetism to devices and research areas in applied physics.

APPH E3400y Physics of the human body
Prerequisite(s): PHYS UN1201 or UN1401, and Calculus I. Corequisite(s): PHYS UN1202 or UN1402, and Calculus II. This introductory course analyzes the human body from the basic principles of physics. Topics covered include the energy balance in the body, the mechanics of motion, fluid dynamics of the heart and circulation, vibrations in speaking and hearing, muscle mechanics, gas exchange and transport in the lungs, vision, structural properties and limits, electrical properties and the development and sensing of magnetic fields, and basics of equilibrium and regulatory control. In each case, a simple model of the body organ, property, or function will be derived and then applied.

APPH E3900x and y Undergraduate research in applied physics
0–4 pts. Members of the faculty.
Prerequisite(s): Written permission from instructor and approval from adviser. May be repeated for credit, but no more than 6 points may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in applied physics or carry out a special project under the supervision of the staff. Credit for course is contingent upon the submission of an acceptable thesis or final report.

APAM E3999x, y or s Undergraduate fieldwork
1–2 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from adviser. Restricted to ENAPMA, ENAPPH, ENMSAE. May be repeated for credit, but no more than 3 total points may be used toward the 128-credit degree requirement. Only for APAM undergraduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation required. Fieldwork credits may not

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count toward any major core, technical, elective, or nontechnical requirements. May not be taken for pass/fail credit or audited.

APPH E4010x Introduction to nuclear science
3 pts. Lect. 3. Professor Ostroum. Prerequisite(s): MATH UN1020 or APMA E2000, and UN2030 and PHYS UN103 or equivalents. Introductory course for individuals with an interest in medical physics and other branches of radiation science. Topics include basic concepts, nuclear models, semiempirical mass formula, interaction of radiation with matter, nuclear detectors, nuclear structure and instability, radioactive decay process and radiation, particle accelerators, and fission and fusion processes and technologies.

APPH E4018y Applied physics laboratory
2 pts. Lab. 4. Members of the faculty. Prerequisite(s): APPH E3300 or ELEN E3401 or equivalent. Typical experiments are in the areas of plasma physics, microwaves, laser applications, optical spectroscopy physics, and superconductivity.

APCH E4080x Soft condensed matter
3 pts. Lect. 3. Professor Gang. Prerequisite(s): MSAE E3111, CHEE E3010, or equivalent. Course is aimed at senior undergraduate and graduate students. Introduces fundamental ideas, concepts, and approaches in soft condensed matter with emphasis on biomolecular systems. Covers the broad range of molecular, nanoscale, and colloidal phenomena with revealing their mechanisms and physical foundations. The relationship between molecular architecture and interactions and macroscopic behavior are discussed for the broad range of soft and biological matter systems, from surfactants and liquid crystals to polymers, nanoparticles, and biomolecules. Modern characterization methods for soft materials, including X-ray scattering, molecular force probing, and electron microscopy are reviewed. Example problems, drawn from the recent scientific literature, link the studied materials to the actively developed research areas. Course grade based on midterm and final exams, weekly homework assignments, and final individual/team project.

APPH E4100x Quantum physics of matter
3 pts. Lect. 3. Professor Venkataraman. Prerequisite(s): APPH E3100. Corequisite(s): APMA E3102 or equivalent. Basic theory of quantum mechanics, well and barrier problems, the harmonic oscillator, angular momentum identical particles, quantum statistics, perturbation theory and applications to the quantum physics of atoms, molecules, and solids.

APPH E4110x Modern optics
3 pts. Lect. 3. Professor Yu. Prerequisite(s): APPH E3300. Ray optics, matrix formulation, wave effects, interference, Gaussian beams, Fourier optics, diffraction, image formation, electromagnetic theory of light, polarization and crystal optics, coherence, guided wave and fiber optics, optical elements, photons, selected topics in nonlinear optics.

APPH E4112x Laser physics
3 pts. Lect. 3. Professor Yu. Recommended but not required: APPH E3100 and E3300 or their equivalents. Optical resonators, interaction of radiation and atomic systems, theory of laser oscillation, specific laser systems, rate processes, modulation, detection, harmonic generation, and applications.

APPH E4114y Quantum and nonlinear photonics
3 pts. Lect. 3. Professor Gaeta. Prerequisite(s): APPH E3300 and PHYS UN3008. Advanced senior-level/M.S./Ph.D. course covering interaction of laser light with matter in both classical and quantum domains. First half introduces microscopic origin of optical nonlinearities through formal derivation of nonlinear susceptibilities, emphasis on second- and third-order optical processes. Topics include Maxwell’s wave equation, and nonlinear optical processes such as second-harmonic, difference-frequency generation, four-wave mixing, and self-phase modulation, including various applications of processes such as frequency conversion, and optical parametric amplifiers and oscillators. Second half describes two-level atomic systems and quantization of electromagnetic field. Descriptions of coherent, Fock, and squeezed states of light discussed and techniques to generate such states outlined.

CHAP E4120y Statistical mechanics
3 pts. Lect. 3. Professor O’Shaughnessy. Prerequisite(s): CHEE E3010 or equivalent or thermodynamics course, or instructor’s permission. Fundamental principles and underlying assumptions of statistical mechanics. Boltzmann’s entropy hypothesis and its restatement in terms of Helmholtz and Gibbs free energies and for open systems. Correlation times and lengths. Exploration of phase space and observation time scale. Correlation functions. Fermi-Dirac and Bose-Einstein statistics. Fluctuation-response theory. Applications to ideal gases, interfaces, liquid crystals, microemulsions and other complex fluids, polymers, Coulomb gas, interactions between charged polymers and charged interfaces, ordering transitions.

APPH E4130x Physics of solar energy
3 pts. Lect. 3. Professor Chen. Prerequisite(s): General physics (PHYS UN1043 or UN1602) and mathematics, including ordinary differential equations and complex numbers (such as MATH UN1202 or UN2030) or instructor’s permission. The physics of solar energy including solar radiation, the analemma, atmospheric effects, thermodynamics of solar energy, physics of solar cells, energy storage and transmission, and physics and economics in the solar era.

APPH/CHEM E/GU 4164x Electric field effects in catalysis
1.5 pts. Lect. 2.5. Professors Berkelbach, Nuckolls, Rovis, Roy, and Venkataraman. Prerequisite(s): physical chemistry or equivalent. Real-time exposition of an emerging area of study at the interface between chemistry, physics, engineering, and biology to understand and control how electric fields can be used to catalyze chemical transformations. Taught by a cross-disciplinary group of faculty. Topics covered: (1) theoretical underpinnings for catalysis in nanoscale electric environments, (2) experimental tools used to study these chemical transformations, (3) experimental demonstrations of catalysis in electric fields. Each topic will draw on elements of organometallic/organic catalysis, quantum mechanics, enzymatic catalysis, and nano electronic to form the basis for understanding this new branch of catalytic science.

APPH E4200x Fluids of physics

APPH E4210y Geophysical fluid dynamics
3 pts. Lect. 3. Professor Polvani. Prerequisite(s): APMA E3101, E3102 (or equivalents) and APPH E4200 (or equivalent), or permission from instructor. Fundamental concepts in the dynamics of rotating, stratified flows. Geostrophic and hydrostatic balances, potential vorticity, f and beta plane approximations, gravity and Rossby waves, geostrophic adjustment and quasigeostrophic, baroclinic and barotropic instabilities, Sverdrup balance, boundary currents, Ekman layers.

APPH E4300x Applied electrodynamics
3 pts. Lect. 3. Professor Gaeta. Prerequisite(s): APPH E3300. Overview of properties and interactions of static electric and magnetic fields. Study of phenomena of time dependent electric and magnetic fields including induction, waves, and radiation as well as special relativity. Applications are emphasized.

APPH E4330y Radiobiology for medical physicists
3 pts. Lect. 3. Professor Zaider. Prerequisite(s): APPH E4010 or equivalent or Corequisite(s): APPH E4010. Interface between clinical practice and quantitative radiation biology. Microdosimetry, dose-rate effects and biological effectiveness thereof; radiation biology data, radiation action at the cellular and tissue level; radiation effects on human populations, carcinogenesis, genetic effects; radiation protection; tumor control, normal-tissue complication probabilities; treatment plan optimization.

APPH E4500y Health physics
3 pts. Lect. 3. Professor Caracappa. Prerequisite(s): APPH E4600 or Corequisite(s): APPH E4600. Fundamental principles and objectives of health physics (radiation protection), quantities of radiation dosimetry (the absorbed dose, equivalent dose, and effective dose) used to evaluate human radiation risks, elementary shielding calculations and protection measures for clinical environments, characterization and proper
use of health physics instrumentation, and regulatory and administrative requirements of health physics programs in general and as applied to clinical activities.

APPH E4550y Medical physics seminar
0 pts. Lect: 1. Professor Wuu.
Required for all graduate students in the Medical Physics Program. Practicing professionals and faculty in the field present selected topics in medical physics.

APPH E4600x Fundamentals of radiological physics and radiation dosimetry
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): APH E4010 or equivalent or Corequisite(s): APH E4010. Basic radiation physics: radioactive decay, radiation producing devices, characteristics of the different types of radiation (photons, charged and uncharged particles) and mechanisms of their interactions with materials. Essentials of the determination, by measurement and calculation, of absorbed doses from ionizing radiation sources used in medical physics (clinical) situations and for health physics purposes.

APPM E4650x Anatomy for physicists and engineers
Prerequisite(s): Engineering or physics background. Systemic approach to the study of the human body from a medical imaging point of view: skeletal, respiratory, cardiovascular, digestive, and urinary systems, breast and women’s issues, head and neck, and central nervous system. Lectures are reinforced by examples from clinical two- and three-dimensional and functional imaging (CT, MRI, PET, SPECT, US, etc.).

APPH E4710x Radiation instrumentation and measurement laboratory, I
Prerequisite or corequisite: APH E4010. Theory and use of alpha, beta, gamma, and X-ray detectors and associated electronics for counting, energy spectroscopy, and dosimetry; radiation safety; counting statistics and error propagation; mechanisms of radiation emission and interaction. (Topic coverage may be revised.)

APPH E4901x Seminar: problems in applied physics
Required for, and can be taken only by, all applied physics majors and minors in the junior year. Discussion of specific and self-contained problems in areas such as applied electrodynamics, physics of solids, and plasma physics. Topics change yearly.

APPH E4903x Seminar: problems in applied physics
Required for, and can be taken only by, all applied physics majors in the senior year. Discussion of specific and self-contained problems in areas such as applied electrodynamics, physics of solids, and plasma physics. Formal presentation of a term paper required. Topics change yearly.

APPH E4990x and y Special topics in applied physics
1–3 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. May be repeated for credit. Topics and instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

APAM E4999x and y–S4999 Supervised internship
1–3 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from adviser. Only for master’s students in the Department of Applied Physics and Applied Mathematics who may need relevant work experience as part of their program of study. Final report required. May not be taken for pass/fail or audited.

APPH E6081x Solid state physics, I
Prerequisite(s): APPH E4010 or the equivalent. Knowledge of statistical physics on the level of MSAE E3111 or PHYS GU4023 strongly recommended. Crystal structure, reciprocal lattices, classification of solids, lattice dynamics, anharmonic effects in crystals, classical electron models of metals, electron band structure, and low-dimensional electron structures.

APPH E6101x Plasma physics, I
3 pts. Lect: 3. Professor Navratil.
Prerequisite(s): APPH E4300 or the equivalent. Linear electrostatic and electromagnetic waves in unmagnetized and magnetized plasmas. The magnetohydrodynamic (MHD) model, including MHD equilibrium, stability, and MHD waves in simple geometries.

APPH E6102y Plasma physics, II
3 pts. Lect: 3. Professor Paz-Soldan.

APPH E6110x Laser interactions with matter
Prerequisite(s): APPH E4112 or equivalent, and quantum mechanics. Principles and applications of laser-matter coupling, nonlinear optics, three- and four-wave mixing, harmonic generation, laser processing of surfaces, laser probing of materials, spontaneous and stimulated light scattering, saturation spectroscopy, multiphoton excitation, laser isotope separation, transient optical effects.

APPH E6319y Clinical nuclear medicine physics
3 pts. Lect: 3. Professor Zanzonico.
Prerequisite(s): APPH E4010 or equivalent recommended. Introduction to the instrumentation and physics used in clinical nuclear medicine and PET with an emphasis on detector systems, tomography and quality control. Problem sets, papers, and term project.

APPH E6330y Diagnostic radiology physics
3 pts. Lect: 3. Professor Jambawalikar.
Prerequisite(s): APPH E4600. Physics of medical imaging. Imaging techniques: radiography, fluoroscopy, computed tomography, mammography, ultrasound, magnetic resonance. Includes conceptual, mathematical/theoretical, and practical clinical physics aspects.

APPH E6333x or y Radiation therapy physics practicum
3 pts. Lab: 6. Professor Wuu.
Prerequisite(s): Grade of B+ or better in APPH E6335 and instructor’s permission. Students spend two to four days per week studying the clinical aspects of radiation therapy physics. Projects on the application of medical physics in cancer therapy within a hospital environment are assigned; each entails one or two weeks of work and requires a laboratory report. Two areas are emphasized: 1. computer-assisted treatment planning (design of typical treatment plans for various treatment sites including prostate, breast, head and neck, lung, brain, esophagus, and cervix) and 2. clinical dosimetry and calibrations (radiation measurements for both photon and electron beams, as well as daily, monthly, and part of annual QA).

APPH E6335y Radiation therapy physics
3 pts. Lect: 3. Professor Wuu.
Prerequisite(s): APPH E4600; APPH E4330 recommended. Review of X-ray production and fundamentals of nuclear physics and radioactivity. Detailed analysis of radiation absorption and interactions in biological materials as specifically related to radiation therapy and radiation therapy dosimetry. Surveys of use of teletherapy isotopes and X-ray generators in radiation therapy plus the clinical use of interstitial and intracavitary isotopes. Principles of radiation therapy treatment planning and isodose calculations. Problem sets taken from actual clinical examples are assigned.

APPH E6336x Advanced topics in radiation therapy
3 pts. Lect: 3. Professor Wuu.
Prerequisite(s): APPH E6335. Advanced technology applications in radiation therapy physics, including intensity modulated, image guided, stereotactic, and hypofractionated radiation therapy. Emphasis on advanced technological, engineering, and quality assurance issues associated with high-technology radiation therapy and the special role of the medical physicist in the safe clinical application of these tools.

APPH E6340x or y Diagnostic radiology physics
Prerequisite(s): Grade of B+ or better in APPH E6330 and instructor’s permission. Practical applications of diagnostic radiology for various measurements and equipment assessments. Instruction and supervised practice in radiation safety procedures, image quality assessments, regulatory compliance, radiation dose evaluations and calibration of equipment. Students participate in clinical QC of the following imaging equipment:
radiologic units (mobile and fixed), fluoroscopy units (mobile and fixed), angiography units, mammography units, CT scanners, MRI units and ultrasound units. The objective is familiarization in routine operation of test instrumentation and QC measurements utilized in diagnostic medical physics. Students are required to submit QC forms with data on three different types of radiology imaging equipment.

APPH E6365x or y Nuclear medicine practicum
3 pts. Lab: 6. Professor Hamacher. Prerequisite(s): Grade of B+ or better in APPH E6319 and instructor’s permission. Practical applications of nuclear medicine theory and application for processing and analysis of clinical images and radiation safety and quality assurance programs. Topics may include tomography, instrumentation, and functional imaging. Reports.

APPH E6380x or y Health physics practicum
3 pts. Lab: 6. Professor Caracappa. Prerequisite(s): Grade of B+ or better in APPH E4500 and instructor’s permission or Corequisite(s): APPH E4500 and permission of the instructor. Radiation protection practices and procedures for clinical and biomedical research environments. Includes design, radiation safety surveys of diagnostic and therapeutic machine source facilities, the design and radiation protection protocols for facilities using unsealed sources of radioactivity—nuclear medicine suites and sealed sources—brachytherapy suites. Also includes radiation protection procedures for biomedical research facilities and the administration of programs for compliance to professional health physics standards and federal and state regulatory requirements for the possession and use of radioactive materials and machine sources of ionizing and nonionizing radiations in clinical situations. Individual topics are decided by the student and the collaborating Clinical Radiation Safety Officer.

APAM E6650x and y–S6650 Research project
1–6 pts. Members of the faculty. Prerequisite(s): Written permission from instructor and approval from adviser. May be repeated for credit. A special investigation of a problem in nuclear engineering, medical physics, applied mathematics, applied physics, and/or plasma physics consisting of independent work on the part of the student and embodied in a formal report.

APPH E9142x-E9143y Applied physics seminar
3 pts. Sem: 3. Members of the faculty. These courses may be repeated for credit. Selected topics in applied physics. Topics and instructors change from year to year.

APAM E9301x Doctoral research
0–15 pts. Members of the faculty. Prerequisite(s): Qualifying examination for the doctorate. Required of doctoral candidates.

APAM E9800x Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty. A candidate for the Eng.Sc.D. degree must register for 12 points of doctoral research instruction. Registration for APAM E9800 may not be used to satisfy the minimum residence requirement for the degree.

APAM E9900x Doctoral dissertation
0 pts. Members of the faculty. A candidate for the doctorate may be required to register for this course every term after the coursework has been completed, and until the dissertation has been accepted.

COURSES IN APPLIED MATHEMATICS

APMA E2000x and y Multivariable calculus for engineers and applied scientists
4 pts. Lect: 3. Professors Youngren and Tong. Differential and integral calculus of multiple variables. Topics include partial differentiation; optimization of functions of several variables; line, area, volume, and surface integrals; vector functions and vector calculus; theorems of Green, Gauss, and Stokes; applications to selected problems in engineering and applied science.

APMA E2001x and y Multivariable calculus for engineers and applied scientists
0 pts. Professors Youngren and Tong. Required recitation session for students enrolled in APMA E2000.

APMA E2101y Introduction to applied mathematics
3 pts. Lect: 3. Professor He. Prerequisite(s): Calculus III. A unified, single-semester introduction to differential equations and linear algebra with emphases on (1) elementary analytical and numerical technique and (2) discovering the analogs on the continuous and discrete sides of the mathematics of linear operators: superposition, diagonalization, fundamental solutions. Concepts are illustrated with applications using the language of engineering, the natural sciences, and the social sciences. Students execute scripts in Mathematica and MATLAB (or the like) to illustrate and visualize course concepts (programming not required).

APAM - HSAM W2901y Data: past, present and future
3 pts. Lect: 1.5. Lab: 1.5. Professors Wiggins and Jones. Prerequisite(s): Instructor’s permission. Critical thinking and practice regarding the past, present, and future of data. Readings covering how students, scholars, and citizens can make sense of data in science, public policy, and our personal lives. Labs covering descriptive, predictive, and prescriptive modeling of data.

APMA E3101x Linear algebra

APMA E3102y Partial differential equations

APMA E3900x and y Undergraduate research in applied mathematics
0–4 pts. Members of the faculty. Prerequisite(s): Written permission from instructor and approval from adviser. May be repeated for credit, but no more than 6 points may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in applied mathematics or carry out a special project under the supervision of the staff. Credit for the course is contingent upon the submission of an acceptable thesis or final report.

APMA E4007x Applied linear algebra
3 pts. Lect: 3. Professor Tippett. Prerequisite(s): Course cannot be taken together with APMA E3101. Fundamentals of linear algebra, including vector and Matrix algebra, solution of linear systems, existence and uniqueness, gaussian elimination, Gauss-Jordan elimination, the matrix inverse, elementary matrices and the LU factorization, computational cost of solutions. Vector spaces and subspaces, linear independence, basis and dimension. The four fundamental subspaces of a matrix. Orthogonal projection onto a subspace and solution of Linear Least Squares problems, unitary matrices, inner products, orthogonalization algorithms and QR factorization, applications. Determinants and applications. Eigen problems, including diagonalization, symmetric matrices, positive-definite systems, eigen factorization and applications to dynamical systems and iterative maps. Introduction to singular value decomposition and its applications.

APMA E4008y Advanced linear algebra
3 pts. Lect: 3. Professor He. Prerequisite(s): APMA E3101 or E4007. Advanced topics in linear algebra with applications to data analysis, algorithms, dynamics and differential equations, and more. (1) General vector spaces, linear transformations, spaces isomorphisms; (2) spectral theory - normal matrices and their spectral properties, Rayleigh quotient, Courant-Fischer Theorem, Jordan forms, eigenvalue perturbations; (3) least square problem and Gauss-Markov Theorem; (4) singular value decomposition, its approximation properties, matrix norms, PCA and CCA.
APMA E4101y Introduction to dynamical systems
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): APMA E3101 or MATH UN2010 (Linear Algebra), and MATH UN2030 (ODE), or their equivalents, or instructor’s permission.
An introduction to the analytic and geometric theory of dynamical systems; basic existence, uniqueness and parameter dependence of solutions to ordinary differential equations; constant coefficient and parametrically forced systems; Fundamental solutions; resonance; limit points, limit cycles and classification of flows in the plane (Poincare-Bendixon Theorem); conservative and dissipative systems; linear and nonlinear stability analysis of equilibria and periodic solutions; stable and unstable manifolds; bifurcations, e.g., Andronov-Hopf; sensitive dependence and chaotic dynamics; selected applications.

APMA E4150y Applied functional analysis
3 pts. Lect: 3. Professor Weinstein.
Prerequisite(s): Advanced calculus and course in basic analysis, or instructor’s permission.
Introduction to modern tools in functional analysis that are used in the analysis of deterministic and stochastic partial differential equations and in the analysis of numerical methods: metric and normed spaces, Banach space of continuous functions, measurable spaces, the contraction mapping theorem, Banach and Hilbert spaces bounded linear operators on Hilbert spaces and their spectral decomposition, and time permitting distributions and Fourier transforms.

APMA E4200x and y Partial differential equations
3 pts. Lect: 3. Professor Du and Members of the faculty.

APMA E4204x Functions of a complex variable
3 pts. Lect. 3. Professor Ren.
Prerequisite(s): MATH UN1202 or APMA E2000 or equivalent. Complex numbers, functions of a complex variable, differentiation and integration in the complex plane. Analytic functions, Cauchy integral theorem and formula, Taylor and Laurent series, poles and residues, branch points, evaluation of contour integrals. Conformal mapping. Schwarz-Christoffel transformation. Applications to physical problems.

APMA E4300x and y Computational math: introduction to numerical methods
3 pts. Lect: 3. Professor Mandli.
Prerequisite(s): MATH UN1201 or APMA E2000, UN2030, and APMA E3101 and ENGI E1006 or their equivalents. Programming experience in Python extremely useful. Introduction to fundamental algorithms and analysis of numerical methods commonly used by scientists, mathematicians, and engineers. Designed to give a fundamental understanding of the building blocks of scientific computing that will be used in more advanced courses in scientific computing and numerical methods for PDEs (e.g., APMA E4301, APMA E4302). Topics include numerical solutions of algebraic systems, linear least-squares, eigenvalue problems, solution of nonlinear systems, optimization, interpolation, numerical integration and differentiation, initial value problems, and boundary value problems for systems of ODE’s. All programming exercises will be in Python.

APMA E4301y Numerical methods for partial differential equations
Prerequisite(s): APMA E4300 and APMA E3102 or APMA E4200 or equivalents. Numerical solution of differential equations, in particular partial differential equations arising in various fields of application. Presentation emphasizes finite difference approaches to present theory on stability, accuracy, and convergence with minimal coverage of alternate approaches (left for other courses). Method coverage includes explicit and implicit time-stepping methods, direct and iterative solvers for boundary-value problems.

APMA E4302x Methods in computational science
Prerequisite(s): APMA E4300, application and knowledge in C, Fortran or similar compiled language. Introduction to the key concepts and issues in computational science aimed at getting students to a basic level of understanding where they can run simulations on machines aimed at a range of applications and sizes from a single workstation to modern super-computer hardware. Topics include but are not limited to basic knowledge of unix shells, version control, OpenMP, MPI, and many-core technologies. Applications will be used throughout to demonstrate the various use cases and pitfalls of using the latest computing hardware.

APMA E4306y Applied stochastic analysis
3 pts. Lect: 3. Professor Ren.
Prerequisite(s): Elementary probability theory (IEOR E3658 or above) and stochastic process (on the level of the first part of IEOR E4106 or STAT G4264) are required. Knowledge on analysis (MATH GU4601 or above) and differential equations (APMA E4200 or above) are required. Knowledge on numerical methods (APMA E4300 and above) and programming skills are required. Provides elementary introduction to fundamental ideas in stochastic analysis for applied mathematics. Core material includes: (1) review of probability theory (including limit theorems), and introduction to discrete Markov chains and Monte Carlo methods; (2) elementary theory of stochastic process, Ito’s stochastic calculus, and stochastic differential equations; (3) introductions to probabilistic representation of elliptic partial differential equations (the Kolmogorov-Planck equation theory); (4) stochastic approximation algorithms; and (5) asymptotic analysis of SDEs.

APMA E4901y Seminar: problems in applied mathematics
0 pts. Lect: 1. Professor Wiggins.
Required for, and can be taken only by, all applied mathematics majors in the junior year. Introductory seminars on problems and techniques in applied mathematics. Typical topics are nonlinear dynamics, scientific computation, economics, operations research, etc.

APMA E4903x Seminar: problems in applied mathematics
Required for all applied mathematics majors in the senior year. Term paper required. Examples of problem areas are nonlinear dynamics, asymptotics, approximation theory, numerical methods, etc. Approximately three problem areas are studied per term.

APMA E4990x and y Special topics in applied mathematics
1–3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Advanced calculus and junior year applied mathematics, or their equivalents. May be repeated for credit. Topics and instructors from the Applied Mathematics Program and the staff change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, biological sciences, and other fields. Examples of topics include multiscale analysis and Applied Harmonic Analysis.

APMA E6100x or y Research seminar
0 pts. Lect: 1. Professor Ren.
Prerequisite(s): MATH UN3027 or APMA E4101, MATH UN3028 or APMA E4200, MATH UN2010 or APMA E3101 or their equivalents. An M.S. degree requirement. Students attend at least three Applied Mathematics research seminars within the Department of Applied Physics and Applied Mathematics and submit reports on each.

APMA E6301x Analytic methods for partial differential equations
Prerequisite(s): Advanced calculus, basic concepts in analysis, APMA E3101 or E4200 or their equivalents, or instructor’s permission. Introduction to analytic theory of PDEs of fundamental and applied science; wave (hyperbolic), Laplace and Poisson equations (elliptic), heat (parabolic) and Schroedinger (dispersive) equations; fundamental solutions, maximum principle, energy estimates, scale analysis and Applied Harmonic Analysis.

APMA E6302x Analytic methods for partial differential equations
Prerequisite(s): Advanced calculus, basic concepts in analysis, APMA E3101 or E4200 or their equivalents, or instructor’s permission. Introduction to analytic theory of PDEs of fundamental and applied science; wave (hyperbolic), Laplace and Poisson equations (elliptic), heat (parabolic) and Schroedinger (dispersive) equations; fundamental solutions, maximum principle, energy estimates, variational methods, method of characteristics; elementary functional analysis and applications to PDEs; introduction to nonlinear PDEs, shocks; selected applications.

APMA E6302y Numerical analysis of partial differential equations
3 pts. Lect: 2. Professor Du.
Prerequisite(s): APMA E3102 or E4200. Numerical analysis of initial and boundary value problems for partial differential equations. Convergence and stability of the finite difference method, the spectral method, the finite element method and applications to elliptic, parabolic, and hyperbolic equations.
APMA E6901x and y–E6901y Special topics in applied mathematics
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Advanced calculus and junior year applied mathematics, or their equivalents. May be repeated for credit. Topics and instructors from the Applied Mathematics Program and the staff change from year to year. For students in engineering, physical sciences, biological sciences, and other fields. Examples of topics include uncertainty quantification.

APMA E9101x-E9102y Research
1–4 pts. Members of the faculty.
Prerequisite(s): Permission of the supervising faculty member. May be repeated. Advanced study in a special area.

APMA E9810x or y SEAS colloquium in climate science
0 pts. Lect: 1. Professors Polvani and Sobel.
Prerequisite(s): Instructor’s permission. Current research in problems at the interface between applied mathematics and earth and environmental sciences.

APMA E9815x or y Geophysical fluid dynamics seminar
1–3 pts. May be repeated for up to 10 points of credit. Not offered in 2022–2023.
Prerequisite(s): Instructor’s permission. Problems in the dynamics of geophysical fluid flows.

COURSES IN MATERIALS SCIENCE AND ENGINEERING
See page 183.
Biomedical engineering is an evolving discipline in engineering that draws on collaboration among engineers, physicians, and scientists to provide interdisciplinary insight into medical and biological problems. The field has developed its own knowledge base and principles that are the foundation for the academic programs designed by the Department of Biomedical Engineering at Columbia.

The programs in biomedical engineering at Columbia (B.S., M.S., Ph.D., Eng.Sc.D., and M.D./Ph.D.) prepare students to apply engineering and applied science to problems in biology, medicine, and the understanding of living systems and their behavior, and to develop biomedical systems and devices. Modern engineering encompasses sophisticated approaches to measurement, data acquisition and analysis, simulation, and systems identification. These approaches are useful in the study of individual cells, organs, entire organisms, and populations of organisms. The increasing value of mathematical models in the analysis of living systems is an important sign of the success of contemporary activity. The programs offered in the Department of Biomedical Engineering seek to emphasize the confluence of basic engineering science and applied engineering with the physical and biological sciences, particularly in the areas of biomechanics, cell and tissue engineering, and biosignals and biomedical imaging.

Programs in biomedical engineering are taught by its own faculty, members of other Engineering departments, and faculty from other University divisions who have strong interests and involvement in biomedical engineering. Several of the faculty hold joint appointments in Biomedical Engineering and other University departments.

Courses offered by the Department of Biomedical Engineering are complemented by courses offered by other departments in The Fu Foundation School of Engineering and Applied Science and by many departments in the Faculty of Medicine, the College of Dental Medicine, and the Mailman School of Public Health, as well as the science departments within the Graduate School of Arts and Sciences. The availability of these courses in a university that contains a large medical...
center and enjoys a basic commitment to interdisciplinary research is important to the quality and strength of the program.

Educational programs at all levels are based on engineering and biological fundamentals. From this basis, the program branches into concentrations of contemporary biomedical engineering fields. The intrinsic breadth of these concentrations, and a substantial elective content, prepare bachelor's and master's students to commence professional activity in any area of biomedical engineering or to go on to graduate school for further studies in related fields. The program also provides excellent preparation for the health sciences and the study of medicine. Graduates of the doctoral program are prepared for research activities at the highest level.

Areas of particular interest to Columbia faculty include biomechanics (Professors Ateshian, Guo, Hess, Morrison, and Nerurkar), cellular and tissue engineering (Professors Arinzeh, Correa, Danino, Hung, Kam, Leong, Lu, Morrison, Sia, and Vunjak-Novakovic), auditory biophysics (Professor Olson), biomaterials (Professors Arinzeh, Correa, Danino, Hess, Kam, Leong, Lu, Sia, and Vunjak-Novakovic), biosignals and biomedical imaging (Professors Guo, Hillman, Jacobs, Juchem, Konofagou, Laine, Sajda, Vaughan, and Wang), neuroengineering (Professors Hillman, Jacobs, Konofagou, Laine, Morrison, Sajda, and Wang) and machine learning (Azizi, Laine, Sajda, Vickovic).

Facilities
The Department of Biomedical Engineering has been supported by grants obtained from NIH, NSF, DoT, DoD, New York State, numerous research foundations, and University funding. The extensive facilities that are at the Medical Center, Manhattanville, and Morningside campuses include teaching and research laboratories that provide students with unusual access to contemporary research equipment specially selected for its relevance to biomedical engineering. Another addition is an undergraduate wet laboratory devoted to biomechanics and cell and tissue engineering, together with a biosignals and biomedical imaging and data processing laboratory. Each laboratory incorporates equipment normally reserved for advanced research and provides exceptional access to current practices in biomedical engineering and related sciences.

Research facilities of the Biomedical Engineering faculty include the Computational Cancer Biology Laboratory (Professor Azziz), the Synthetic Biological Systems Laboratory (Professor Danino), the Heffner Biomedical Imaging Laboratory (Professor Laine), the Laboratory for Intelligent Imaging and Neural Computing (Professor Sajda), the Bone Bioengineering Laboratory (Professor Guo), the Cellular Engineering Laboratory (Professor Hung), the Biomaterial and Interface Tissue Engineering Laboratory (Professor Lu), the Neurotrauma and Repair Laboratory (Professor Morrison), the Laboratory for Stem Cells and Tissue Engineering (Professor Vunjak-Novakovic), the Ultrasound and Elasticity Imaging Laboratory (Professor Konofagou), the Magnetic Resonance Scientific Engineering for Clinical Excellence Laboratory (Professor Juchem), the Microscale Biocomplexity Laboratory (Professor Kam), the Molecular and Microscale Bioengineering Laboratory (Professor Sia), the Laboratory for Functional Optical Imaging (Professor Hillman), the Cognitive Electrophysiology Laboratory (Professor J. Jacobs), the Nanobiotechnology and Synthetic Biology Laboratory (Professor Hess), the Raymond and Beverly Sackler Laboratory for Neural Engineering and Control (Professor Wang), the Morphogenesis and Developmental Biomechanics Lab (Professor Nerurkar), and the Laboratory for Nanomedicine and Regenerative Medicine (Professor Leong). These laboratories are supplemented with core facilities, including a tissue culture facility, a histology facility, a confocal microscope, an atomic force microscope, a 2-photon microscope, epifluorescence microscopes, a freezer room, biomechanics facilities, a machine shop, and a specimen preparation room.

UNDERGRADUATE PROGRAM
The program in biomedical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET, http://www.abet.org. The objectives of the undergraduate program in biomedical engineering are as follows:

1. Professional employment in areas such as the medical device industry, engineering consulting, and biotechnology;
2. Graduate studies in biomedical engineering or related fields;
3. Attendance at medical, dental, or other professional schools.

The undergraduate program in biomedical engineering will prepare graduates who will have:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on teams whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

The undergraduate curriculum is designed to provide broad knowledge of the physical and engineering sciences and their application to the solution of biological and medical problems. Students are strongly encouraged to take courses in the order specified in the course tables; deviations must be discussed with a departmental adviser and approved by the department before registration. The first two years provides a strong grounding in the physical and chemical
First and Second Years
As outlined in this bulletin, in the first two years, all engineering students are expected to complete a sequence of courses in mathematics, physics, chemistry, computer science, engineering, modern biology, English composition, and physical education, as well as nontechnical electives including the humanities. For most of these sequences, the students may choose from two or more tracks. If there is a question regarding the acceptability of a course as a nontechnical elective, please consult the approved listing of courses beginning on page 9 or contact your advising dean for clarification.

Please see the charts in this section for a specific description of course requirements.

For students who are interested in the biomedical engineering major, they must take E1201: Introduction to electrical engineering. For the computer science requirement, students must take ENGI E1006. They must take the two-semester BIOL UN2005 and UN2006: Introduction to Biology I & II in the second year, which gives students a comprehensive overview of modern biology from molecular to organ system levels. In addition, all students must take APMA E2101: Introduction to applied mathematics in their second year.

Third and Fourth Years
The biomedical engineering programs at Columbia are based on engineering and biological fundamentals. This is emphasized in our core requirements, which cannot be waived nor substituted. All students must take the two-semester introduction to biomedical engineering courses, BMEN E3010 and E3020. Biomedical engineering I & II, which provide a broad yet solid foundation in the biomedical engineering discipline. In parallel, all students take the two-semester Quantitative physiology, I and II sequence (BMEN E4001-E4002), which is taught by biomedical engineering faculty and emphasizes quantitative applications of engineering principles in understanding biological systems and phenomena from molecular to organ system levels. In the fields of biomedical engineering, experimental techniques and principles are fundamental skills that good biomedical engineers must master.

Beginning in junior year, all students take the two-semester sequence Biomedical engineering laboratory, I & II (BMEN E3810, E3820). In this two-semester series, students learn through hands-on experience the principles and methods of biomedical engineering experimentation, measurement techniques, quantitative theories of biomedical engineering, data analysis, and independent design of biomedical engineering experiments, in parallel to the Biomedical engineering I & II and Quantitative physiology I & II courses. In addition, all students must take BMEN E4110: Biostatistics for engineers. In the senior year, students are required to take a two-semester capstone design course, Biomedical engineering design (BMEN E3910 and E3920), in which students work within a team to tackle an open-ended design project in biomedical engineering. The underlying philosophy of these core requirements is to provide our biomedical engineering students with a broad knowledge and understanding of topics in the field of biomedical engineering.

Parallel to these studies in core courses, students are required to take flexible technical elective courses (21 points) to obtain an in-depth understanding of their chosen interests. A technical elective is defined as a 3000-level or above course taught in SEAS or 3000-level or above courses in biology, chemistry, biochemistry, or biotechnology. Exceptions include organic chemistry lecture courses and laboratory (which are 2000-level courses). At least 15 points (five courses) of these technical electives must have engineering content, while at least two of the five courses have to be from the Department of Biomedical Engineering. The curriculum prepares students who wish to pursue careers in medicine by satisfying most requirements in the premedical programs with no more than three additional courses. Some of these additional courses may also be counted as nongraduate technical electives. Please see the course tables for schedules leading to a bachelor’s degree in biomedical engineering.

It is strongly advised that students take required courses during the specific term that they are designated in the course tables, as scheduling conflicts may arise if courses are taken out of sequence.

**Note:** The text is a continuation of the previous content and provides a detailed description of the curriculum, requirements, and course offerings for biomedical engineering students at Columbia University.
Technical Elective Requirements

Students are required to take at least 48 points of engineering content coursework toward their degree. The 48-point requirement is a criterion established by ABET. Taking into consideration the number of engineering content points conferred by the required courses of the BME curriculum, a portion of technical electives must be clearly engineering in nature (Engineering Content Technical Electives), specifically as defined below:

1. Technical elective courses with sufficient engineering content that can count toward the 48 units of engineering courses required for ABET accreditation:
   a. All 3000-level or higher courses in the Department of Biomedical Engineering, except BMEN E4010, E4103, E4104, E4105, E4106, E4107, E4108, and E6510; additionally, BMEN E4000 001 in fall 2019. (Note that only 3 points of BMEN E3998 may be counted toward technical engineering degree requirements.)
   b. All 3000-level or higher courses in the Department of Mechanical Engineering, except MECE E4007: Creative engineering and entrepreneurship
   c. All 3000-level or higher courses in the Department of Chemical Engineering, except CHEN E4020: Safeguarding intellectual and business property
   d. All 3000-level or higher courses in the Department of Electrical Engineering, except EEHS E3900: History of telecommunications: from the telegraph to the internet
   e. All 3000-level or higher courses

**Technical Elective Requirements**

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   b. All 3000-level or higher courses in the Department of Mechanical Engineering, except MECE E4007: Creative engineering and entrepreneurship
   c. All 3000-level or higher courses in the Department of Chemical Engineering, except CHEN E4020: Safeguarding intellectual and business property
   d. All 3000-level or higher courses in the Department of Electrical Engineering, except EEHS E3900: History of telecommunications: from the telegraph to the internet
   e. All 3000-level or higher courses
BIOMEDICAL ENGINEERING: THIRD AND FOURTH YEARS

<table>
<thead>
<tr>
<th>REQUIRED COURSES</th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BMEN E3010 (3) Biomedical eng., I</td>
<td>BMEN E3020 (3) Biomedical eng., II</td>
<td>BMEN E3910 (4) BME design, I</td>
<td>BMEN E3920 (4) BME design, II</td>
</tr>
<tr>
<td></td>
<td>BMEN E3810 (3) BME laboratory, I</td>
<td>BMEN E3820 (3) BME laboratory, II</td>
<td>Technical elective (3)¹</td>
<td>Technical elective (3)¹</td>
</tr>
<tr>
<td></td>
<td>BMEN E4001 (3) Quantitative physiol., I</td>
<td>BMEN E4002 (3) Quantitative physiol., II</td>
<td>Technical elective (3)¹</td>
<td>Technical elective (3)¹</td>
</tr>
<tr>
<td></td>
<td>BMEN E4110 (4) Biostat. for engineers</td>
<td>Technical elective (3)¹</td>
<td>Technical elective (3)¹</td>
<td>Technical elective (3)¹</td>
</tr>
<tr>
<td>NONTECH ELECTIVES</td>
<td>3 points</td>
<td>3 points</td>
<td>3 points</td>
<td>3 points</td>
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<tr>
<td>TOTAL POINTS</td>
<td>16</td>
<td>15</td>
<td>16</td>
<td>13</td>
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</tbody>
</table>

¹ Five of seven technical electives must have engineering content, and two of them must be from the Biomedical Engineering Department.


f. All 3000-level or higher courses in the Earth and Environmental Engineering program.

2. Courses from the following departments are not allowed to count toward the required 48 units of engineering courses:
   a. Department of Applied Physics and Applied Mathematics
   b. Department of Computer Science
   c. Department of Industrial Engineering and Operations Research
   d. Program of Materials Science and Engineering

Once 48 points of engineering content are satisfied, students may choose any course above the 3000 level in Columbia Engineering as well as biology, chemistry, biochemistry, and biotechnology as technical electives.

If the 3000-level course is greater than or equal to the course cross listed, its eligibility as an engineering content technical elective is determined by the call letters of the first (owning) department in the course name designation. The department owning the course must be ABET accredited to be considered engineering.

For example, APBM E4560 Anatomy for physicists & engineers does not count as engineering content technical elective, since the course is owned by Applied Physics (and cross-listed with Biomedical Engineering). BMCH E4810 Artificial organs is counted as an engineering content technical elective, as the course is owned by Biomedical Engineering (and cross listed with Chemical Engineering).

Based on the above for Engineering Technical Electives, a cross-listed course that is greater than or equal to 3000 level and with BMEN as its starting call letters will qualify as a BME Engineering Technical Elective.

The accompanying charts describe the eight-semester degree program schedule of courses leading to the bachelor's degree in biomedical engineering.

The undergraduate Biomedical Engineering program is designed to provide a solid biomedical engineering curriculum through its core requirements while providing flexibility to meet the individualized interests of the students. All students are encouraged to design their own educational paths through technical electives while meeting the following requirements: (1) courses must be at the 3000-level or above; (2) five of the seven electives must meet the above criteria to be considered engineering content; and (3) two of the seven electives must be biomedical engineering courses. The following grouped courses provide a useful guide for students who wish to focus their studies in a particular Biomedical Engineering topic. The requirements for these elective concentrations are identical to those of the major's course requirements. To declare and earn this designation a student must take at least four of the courses listed for that concentration, and at least two of those must be biomedical engineering courses. It is not necessary to declare a concentration for the B.S. program.

BIOFABRICATION & NANOTECHNOLOGY

MECE E3100: Introduction to mechanics of fluids (3)
MECE E3113: Mechanics of solids (3)
MSAE E4090: Nanotechnology (3)
MECE E4212: Microelectromechanical systems (3)
BMEN E4550: Micro- and nanostructures in cellular engineering (3)
BMEN E4580: Foundations of nanobiotechnology and nanobioscience (3)
BMEN E4590: BioMems: cellular and molecular applications (3)

BIOINFORMATICS & MACHINE LEARNING

BIOL UN3041: Cell biology (3)
COMS W3101: Programming languages (1)
COMS W3137: Data structures and algorithms (4)
BINF G4006: Translational bioinformatics (3)
BINF G4015: Computational systems biology: proteins, networks, function (3)
ECBM E4040: Neural networks and deep learning (3)
ECBM E4060: Introduction to genomic information science and technology (3)
STAT GU4241: Statistical machine learning (3)
COMS W4252: Introduction to computational learning theory (3)
BMEN E4220: Biomedical signal processing and signal modeling (3)
BMEN E4460: Deep learning in biomedical imaging (3)
BMEN E4470: Deep learning in biomedical signal processing (3)
COMS W4701: Artificial Intelligence (3)
CBMF W4761: Computational genomics (3)
COMS W4771: Machine learning (3)
BMEN E4895: Analysis and quantification of medical images (3)

BIOMATERIALS
MSAE E3010: Introduction to materials science (3)
BMEN E4501: Biomaterials and scaffold design (3)
BMEN E4510: Tissue engineering (3)
BMEN E4520: Synthetic biology: principles of genetic circuits (3)
BMEN E4530: Drug and gene delivery (3)
BMEN E4590: Biomems: cellular and molecular applications (3)
MEBM E4710: Morphogenesis shape and structure in biological materials (3)
CHEN E4800: Protein engineering (3)

BIOMECHANICS
MECE E3100: Introduction to mechanics of fluids (3)
ENME E3105: Mechanics (4)
MECE E3113: Mechanics of solids (3)
MECE E3301: Thermodynamics (3)
BMEN E4301: Structure, mechanics and adaptation of bone (3)
BMEN E4302: Biomechanics of soft tissue (3)
BMEN E4310: Solid biomechanics (3)
BMEN E4320: Fluid biomechanics (3)
BMEN E4340: Biomechanics of cells (3)
MEBM E4710: Morphogenesis shape and structure in biological materials (3)
BMEN E4750: Sound and hearing (3)

BIOSENSORS & BIOMEDICAL IMAGING
ELEN E3810: Signals and systems (3.5)
BMEN E4410: Ultrasound in diagnostic imaging (3)
BMEN E4420: Biomedical signal processing and signal modeling (3)
BMEN E4430: Principles of MRI (3)
BMEE E4740: Bioinstrumentation (3)
ELEN E4810: Digital signal processing (3)
BMEN E4894: Biomedical imaging (3)
BMEN E4898: Biophotonics (3)

CELL AND TISSUE ENGINEERING
CHEM UN2443: Organic chemistry I (3.5)
CHEM UN2444: Organics chemistry II (3.5)
BMEN E4210: Driving forces of biological systems (3)
BMEN E4310: Solid biomechanics (3)
BMEN E4501: Biomaterials and scaffold design (3)
BMEN E4510: Tissue engineering (3)
BMEN E4550: Micro- and nanostructures in cellular engineering (3)

DESIGN, INNOVATION, AND ENTREPRENEURSHIP
MECE E3408: Computer graphics and design (3)
ENGI W4100: Research to Revenue (3)
BIOT GU4160: Biotechnology Law (3)

BIOT GU4161: Ethics in Biopharmaceutical Patent and Regulatory Law (3)
BIOT GU4200: Biopharmaceutical Development and Regulation (3)
BIOT GU4201: Biopharmaceutical Development and Regulatory Issues (3)
BMEE E4740: Bioinstrumentation (3)

GENOMICS AND SYSTEMS BIOLOGY
CHBM E4321: The genome and the cell (3)
APMA E4400: Introduction to biological modeling (3)
BMEN E4420: Biosignal process and modeling (3)
BMEN E4520: Synthetic biology: principles of genetic circuits (3)
BMEN E4530: Drug and gene delivery (3)
BMEN E4590: BioMems: cellular and molecular applications (3)
CHEN E4700: Principles of genomic technologies (3)
CHEN E4760: Genomics sequence laboratory (3)
CHEN E4800: Protein engineering (3)

NEURAL ENGINEERING
ELEN E3810: Signals and systems (3.5)
BMEE W4040: Computational neuroscience: circuits in the brain (3)
BMEN E4030: Neural control engineering (3)
BMEN E4050: Electrophysiology of human memory and navigation (0)
BMEN E4310: Solid biomechanics (3)
BMEN E4420: Biosignal process and modeling (3)
BMEN E4430: Principles of MRI (3)
ELEN E4810: Digital signal processing (3)
BMEN E4894: Biomedical imaging (3)

PREMED AND PRE-HEALTH PROFESSIONAL
CHEM UN2443: Organic chemistry I (3.5)
CHEM UN2444: Organic chemistry II (3.5)
CHEM UN2493: Organic chemistry lab (techniques) (0)
CHEM UN2494: Organic chemistry lab (synthesis) (0)
BIOL UN3300: Biochemistry (4)
BMEN E4320: Fluid biomechanics (3)
BMEN E4410: Ultrasound in diagnostic imaging (3)
BMEN E4530: Drug and gene delivery (3)

ROBOTICS AND CONTROL OF BIOLOGICAL SYSTEMS
MECE E3100: Introduction to mechanics of fluids (3)
ENME E3105: Mechanics (4)
MECE E3313: Mechanics of solids (3)
BMEE E4030: Neural control engineering (3)
BMEN E4050: Electrophysiology of human memory and navigation (3)
MEBM E4439: Modeling and identification of dynamic systems (3)
MECE E4602: Introduction to robotics (3)
BMEE E4740: Bioinstrumentation (3)

To meet entrance requirements of most U.S. medical schools, students will need to take BIOL UN3501 Biochemistry: Structure and metabolism (4), CHEM UN2545 Organic chemistry laboratory (3), PHYS UN1493: Introduction to experimental physics (3), and PSYC UN1001: The science of psychology (3) as well.

DUAL DEGREE PROGRAMS
Integrated B.S./M.S. Program in Biomedical Engineering
The B.S./M.S. degree program is open to a select group of Columbia juniors and makes possible the earning of both the B.S. and M.S. degrees in an integrated fashion. Benefits of this program include the matching of graduate courses with the corresponding prerequisites, a greater ability to plan ahead for optimal course planning, and a simplified application process with no GRE required. Up to 6 points from the B.S. degree requirements, specifically BMEN E4001 and E4002, will also count toward fulfilling the M.S. degree course requirements. To qualify for this program, students must have a cumulative GPA of at least 3.4 and should apply for the program by April 30 in their junior year. For more information on requirements and application process, please visit bme.columbia.edu.

M.D./M.S. Program in Biomedical Engineering
The Doctor of Medicine/Master of Science in Biomedical Engineering (M.D./M.S.) program is an integrated program offered between The Fu Foundation School of Engineering and Applied Science and the College of Physicians and Surgeons at Columbia University. The purpose of this program is to supplement the current training of medical students with world-class training in biomedical engineering at the graduate-level. This interdisciplinary educational experience will prepare students to become innovative leaders in science, engineering, and medicine. The program is open to a select group of Columbia medical students and makes possible the earning of both the M.D. and M.S. degree in 5 years (4 years for the M.D. program, 1 year for the M.S. program). Six points from the M.D. degree, through completion of anatomy coursework, will also count toward the Master of Science degree. Students must first be admitted to the College of Physicians and Surgeons at Columbia.
University and then apply separately to the Department of Biomedical Engineering. For more information on requirements and application process, please visit bme.columbia.edu.

GRADUATE PROGRAMS

The graduate curriculum in biomedical engineering is track-free at the master’s level while at the doctoral level, it consists of three tracks: biomechanics, cell and tissue engineering, and biosignals and biomedical imaging. Initial graduate study in biomedical engineering is designed to expand the student’s undergraduate preparation in the direction of the concentration of interest. In addition, sufficient knowledge is acquired in other areas to facilitate broad appreciation of problems and effective collaboration with specialists from other scientific, medical, and engineering disciplines. The Department of Biomedical Engineering offers a graduate program leading to the Master of Science degree (M.S.), the Doctor of Philosophy degree (Ph.D.), and the Doctor of Engineering Science degree (Eng.Sc.D.). Applicants who have a Master of Science degree or equivalent may apply directly to the doctoral degree program. All applicants are expected to have earned the bachelor’s degree in engineering or in a cognate scientific program. The Graduate Record Examination (General Test only) is required of all applicants. Students whose bachelor’s degree was not earned in a country where English is the dominant spoken language are required to take the TOEFL, IELTS, PTE Academic, or Duolingo English Test. In addition, sufficient knowledge is acquired in other areas to facilitate broad appreciation of problems and effective collaboration with specialists from other scientific, medical, and engineering disciplines.

The Department of Biomedical Engineering admits students into the 4-2 program, which provides the opportunity for students holding a bachelor’s degree from certain physical sciences to receive the M.S. degree after two years of study at Columbia.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

CURRICULUM AND EXAM REQUIREMENTS

Master’s Degree

In consultation with an appointed faculty adviser, M.S. students should select a program of 30 points of credit of graduate courses (4000 level or above) appropriate to their career goals. This program must include the course in computational modeling of physiological systems (BMEN E6003); two semesters of BMEN E9700: Biomedical engineering seminar; at least four other biomedical engineering courses where BME is the course’s owning department; and at least one graduate-level course in the Applied Mathematics department. Up to 6 credits of Master’s Research BMEN E9100 may be taken to fulfill degree requirements. Up to 3 credits of coursework outside of SEAS may count towards the MS degree. Students with deficiency in physiology coursework are required to take the BMEN E4001-E4002 sequence before taking BMEN E6003. Candidates must achieve a minimum grade-point average of 2.5. A thesis based on experimental, computational, or analytical research is optional. Students wishing to pursue the Master’s Thesis option are required to complete 6 credits of BMEN E9100 Master’s Research and consult with their BME faculty adviser.

MS concentrations are not required. The following grouped courses are a useful guide for students who wish to focus their studies in a particular Biomedical Engineering topic. If a student chooses to declare a concentration, the requirements for these elective concentrations are identical to those of the standard track (including BMEN 6003, Applied Math, BMEN 9700, four BMEN courses, three SEAS courses, and one 3 credit SEAS/non-SEAS course), with one exception: students must take at least 12 credits from a list of track-specific courses.

BIOINFORMATICS AND MACHINE LEARNING

BMEN G4006: Translational bioinformatics (3)
BMEN G4015: Computational systems biology: proteins, networks, functions (3)
ECBM E4040: Neural networks and deep learning (3)
STAT GU4241: Statistical machine learning (3)
COMS W4252: Introduction to computational learning theory (3)
BMEN E4420: Biomedical signal processing and signal modeling (3)
BMEN E4520: Synthetic biology: principles of genetic circuits (3)
BMEN E4460: Deep learning in biomedical imaging (3)
COMS W4701: Artificial intelligence (3)
CBMF W4761: Computational genomics (3)
COMS W4771: Machine learning (3)
COMS W4772 (E6772): Advanced machine learning (3)
BMEN E4895: Analysis and quantification of medical images (3)
BMEN E9100: Master's research (3)

BIOINFORMATICS AND MACHINE LEARNING

BMEN E4210: Driving forces of biological systems (3)
BMCH E4500: Biological transport and rate processes (3)
BMEN E4501: Biomaterials and scaffold design (3)
BMEN E4510: Tissue engineering (3)
BMEN E4530: Drug and gene delivery (3)
BMEN E4550: Micro- and nanostructures in cellular engineering (3)
BMEN E4580: Fundamentals of nanobioscience and nanobiotechnology (3)
BMEN E4590: BioMems: cellular and molecular applications (3)
BMEN E6001: Current topics in nantotechnology and synthetic biology (3)
BMEN E6500: Tissue and molecular engineering laboratory (3)
BMEN E6505: Advanced biomaterials for tissue engineering (3)
BMEN E9100: Master's research (3)
BIOMECHANICS

MECE E4100: Mechanics of fluids (3)
BMEN E4301: Structure, mechanics, and adaptation of bone (3)
BMEN E4302: Biomechanics of musculoskeletal soft tissues (3)
BMEN E4305: Cardiac mechanics (3)
BMEN E4310: Solid biomechanics (3)
BMEN E4570: Science and engineering of body fluids (3)
BMME E4702: Advanced musculoskeletal biomechanics (3)
MEBM E4703: Molecular mechanics in biology (3)
MEBM E4710: Morphogenesis: shape and structure in biological materials (3)
BMEN E4750: Sound and hearing (3)
MECE E6100: Advanced mechanics of fluids (3)
BMEN E6301: Modeling of biological tissues with finite elements (3)
MEBM E6310-E6311: Mixture theories for biological tissues, I and II (3)
MECE E6422-E6423: Introduction to the theory of elasticity, I and II (3)
MECE E8501: Advanced continuum biomechanics (3)
BMEN E9100: Master’s research (3)

BIOMEDICAL IMAGING

BMEN E4410: Ultrasound in diagnostic imaging (3)
BMEN E4420: Biomedical signal processing and signal modeling (3)
BMEN E4430: Principles of magnetic resonance imaging (3)
BMEE E4740: Bioinstrumentation (3)
ELEN E4810: Digital signal processing (3)
BMEN E4840: Functional imaging for the brain (3)
BMEN E4894: Biomedical imaging (3)
BMEN E4895: Analysis and quantification of medical images (3)
BMEN E4898: Biophotonics (3)
BMEN E5410: Principles and practices of in vivo magnetic resonance spectroscopy (3)
BMEN E9100: Master’s research (3)

NEURAL ENGINEERING

BMEB W4020: Computational neuroscience: circuits in the brain (3)
BMEE E4030: Neural control engineering (3)
BMEN E4050: Electrophysiology of human memory and navigation (3)
BMEN E4420: Biomedical signal processing and signal modeling (3)
BMEN E4430: Principles of magnetic resonance imaging (3)
ELEN E4810: Digital signal processing (3)
BMEN E4894: Biomedical imaging (3)
BMEN E9070: Massively parallel neural computation (3)
BMEN E9100: Master’s research (3)

DESIGN, INNOVATION, AND ENTREPRENEURSHIP

ENGI W4100: Research to revenue (3)
BIOT GU4180: Entrepreneurship in biotechnology (3)
BIOT W4200: Biopharmaceutical development and regulation (3)
IEEM E4200: Intro to human centered design (3)
IEEM E4310: Manufacturing enterprise (3)
MECE E4604: Product design for manufacturability (3)
MECE E4610: Advanced manufacturing processes (3)
IEOR E4570: Entrepreneurship bootcamp (1.5)
BMEN E4740: Bioinstrumentation (3)
BMEN E6005: Biomedical innovation I (3)
BMEN E6006: Biomedical innovation II (3)
BMEN E6007: Lab-to-market: commercializing biomedical innovations (3)

ROBOTICS AND CONTROL OF BIOLOGICAL SYSTEMS

BMEE E4030: Neural control engineering (3)
MECE E4058: Mechatronics and embedded microcomputer control (3)
BMEN E4420: Biomedical signal processing and signal modeling (3)
MEBM E4439: Modeling and identification of dynamic systems (3)
EEME E4601: Digital control systems (3)
MECE E4602: Introduction to robotics (3)
MECS E4603: Applied robotics: algorithms and software (3)
MECE E4606: Digital manufacturing (3)
BMME E4702: Advanced musculoskeletal biomechanics (3)
BMEE E4740: Bioinstrumentation (3)
MECE E6400: Advanced machine dynamics (3)
EEME E6601: Introduction to control theory (3)
EEME E6602: Modern control theory (3)
EEME E6610: Optimal control theory (3)
MECE E6614: Advanced topics in robotics and mechanism synthesis (3)
MECE E6615: Robotic manipulation (3)
BMEN E9100: Master’s research (3)

Doctoral Degree

Doctoral students must complete a program of 30 points of credit beyond the M.S. degree. The core course requirements (9 credits) for the doctoral program include the course in computational modeling of physiological systems (BMEN E6003), plus at least one graduate-level course from the Applied Mathematics department and one graduate-level course in the following departments: Statistics, Applied Mathematics, or a graduate-level Biostatistics course such as BMEN E4110. If BMEN E6003 has already been taken for the master’s degree, a technical elective can be used to complete the core course requirement. If one or both graduate level applied mathematics courses have been taken for the master’s degree, technical elective(s) can be used as a substitution. Students must register for BMEN E9700: Biomedical engineering seminar and for research credits during the first two semesters of doctoral study. Remaining courses should be selected in consultation with the student’s faculty adviser to prepare for the doctoral qualifying examination and to develop expertise in a clearly identified area of biomedical engineering. Students should not receive more than two “C” or below letter grades.

All graduate students admitted to the doctoral degree program must satisfy the equivalent of two semesters’ experience in teaching (one semester for M.D./Ph.D. students). This may include supervising and assisting undergraduate students in laboratory experiments, grading, and preparing lecture materials to support the teaching mission of the department. The requirement must be completed by the 3rd year of graduate studies. The Department of Biomedical Engineering is the only engineering department that offers Ph.D. training to M.D./Ph.D. students. These candidates are expected to complete their Ph.D. program within 3.5 years, with otherwise the same requirements as those outlined for the Doctoral Degree program.

Doctoral Qualifying Examination

Doctoral candidates are required to pass a qualifying examination. This examination is given once a year, and it should be taken after the student has completed 30 points of graduate study. The qualifying examination consists of an oral exam during which the student presents an analysis of assigned scientific papers, as well as answers to questions in topics covering applied mathematics, quantitative biology and physiology, and track-specific material. The committee consists of the thesis adviser and two BME core faculty members approved by the graduate studies committee. A written analysis of the assigned scientific papers must be submitted prior to the oral exam. A minimum cumulative grade-point average of 3.2 without research credit grades is required to register for this examination.

Doctoral Committee and Thesis

Students who pass the qualifying examination must have a core BME faculty member who will serve as their primary research adviser or co-adviser. Each student is expected to submit a research proposal and present it to a committee that consists of three
BME faculty members (two must be core BME faculty members, including research adviser) before the end of year 4. The committee considers the scope of the proposed research, its suitability for doctoral research and the appropriateness of the research plan. The committee may approve the proposal without reservation or may recommend modifications. In general, the student is expected to submit their research proposal after five semesters of doctoral studies. In accordance with regulations of the Graduate School of Arts and Sciences, each student is expected to submit a thesis and defend it before a committee of five faculty, one of whom holds primary appointment in another department or school or university. Every doctoral candidate is required to have had at least one first-author full-length paper accepted for publication in a peer-reviewed journal prior to recommendation for award of the degree.

COURSES IN BIOMEDICAL ENGINEERING

BMEN E1001x Engineering in medicine

BMEN E3010x Biomedical engineering, I
Prerequisite(s): BIOL UN2005 and UN2006. or instructor's permission. Corequisite(s): BMEN E4001, BMEN E3810. Various concepts within the field of biomedical engineering, foundational knowledge of engineering methodology applied to biological and/or medical problems through modules in biomechanics, biomaterials, and cell and tissue engineering.

BMEN E3020y Biomedical engineering, II
3 pts. Lect: 3. Professor Lu.
Prerequisite(s): BIOL UN2005 and UN2006. or instructor's permission. Corequisite(s): BMEN E4002, BMEN E3820. Various concepts within the field of biomedical engineering, foundational knowledge of engineering methodology applied to biological and/or medical problems through modules in biomechanics, bioinstrumentation, and biomedical imaging.

ECBM E3060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Varadan.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. Shares lectures with ECBM E4060, but the work requirements differ somewhat.

BMEN E3810x Biomedical engineering laboratory, I
Fundamental considerations of wave mechanics; design philosophies; reliability and risk concepts; basics of fluid mechanics; design of structures subjected to blast; elements of seismic design; elements of fire design; flood considerations; advanced analysis in support of structural design.

BMEN E3820y Biomedical engineering laboratory, II
3 pts. Lab: 4. Professor Hung.
Biomedical experimental design and hypothesis testing. Statistical analysis of experimental measurements. Analysis of variance, post hoc testing. Fluid shear and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound, characterization of excitable tissues, microfluidics.

BMEN E3910x-E3920y Biomedical engineering design, I and II
A two-semester design sequence to be taken in the senior year. Elements of the design process, with specific applications to biomedical engineering: concept formulation, systems synthesis, design analysis, optimization, biocompatibility, impact on patient health and comfort, health care costs, regulatory issues, and medical ethics. Selection and execution of a project involving the design of an actual engineering device or system. Introduction to entrepreneurship, biomedical start-ups, and venture capital. Semester I: statistical analysis of detection/classification systems (receiver operation characteristic analysis, logistic regression), development of design prototype, need, approach, benefits and competition analysis. Semester II: spiral develop process and testing, iteration and refinement of the initial design/prototype, and business plan development. A lab fee of $100 each is collected.

BMEN E3998x or y Projects in biomedical engineering
1–3 pts. Hours to be arranged. Members of the faculty.
Independent projects involving experimental, theoretical, computational, or engineering design work. May be repeated, but no more than 3 points of this or any other projects or research course may be counted toward the technical elective degree requirements as engineering technical electives.

BMEN E3999x, y or s Fieldwork
1–2 pts. Professor Kam.
Prerequisite(s): Obtained internship and approval from faculty adviser. BMEN undergraduate students only. May be used toward the 128-credit degree requirement. Only for BMEN undergraduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation required. Fieldwork credits may not count toward any major core, technical, elective, and non-technical requirements. May not be taken for pass/fail credit or audited.

BMEN E4000x or y Special topics
3 pts. Lect: 3. Members of the faculty.
Current topics in biomedical engineering. Subject matter will vary by year. Instructors may impose prerequisites depending on the topic.

BMEN E4001x Quantitative physiology, I: cells and molecules
3 pts. Lect: 3. Professor Kam.
Prerequisite(s): BIOL UN2005 and UN2006. Corequisite(s): BMEN E3010 and E3810. Physiological systems at the cellular and molecular level are examined in a highly quantitative context. Topics include chemical kinetics, molecular binding and enzymatic processes, molecular motors, biological membranes, and muscles.

BMEN E4002y Quantitative physiology, II: organ systems
3 pts. Lect: 3. Professor Morrison.
Prerequisite(s): BIOL UN2005 and UN2006. Corequisite(s): BMEN E3020, E3820. Students are introduced to a quantitative, engineering approach to cellular biology and mammalian physiology. Beginning with biological issues related to the cell, the course progresses to considerations of the major physiological systems of the human body (nervous, circulatory, respiratory, renal).

BMEN E4010y Ethics for biomedical engineers
Prerequisite(s): senior status in biomedical engineering or the instructor's permission. Covers a wide range of ethical issues expected to confront graduates as they enter the biotechnology industry, research, or medical careers. Topics vary and incorporate guest speakers from Physicians and Surgeons, Columbia Law School, Columbia College, and local industry.

BMEE W4020x Computational neuroscience: circuits in the brain
3 pts. Lect: 3. Professor Lazar.
Prerequisite(s): ELEN E3801 or BIOL UN3004. The biophysics of computation: modeling biological neurons, the Hodgkin-Huxley neuron, modeling channel conductances and synapses as memristive systems, bursting neurons and central pattern generators, I/O equivalence and spiking neuron models. Information representation and neural encoding: stimulus representation with time.
encoding machines, the geometry of time encoding, encoding with neural circuits with feedback, population time encoding machines. Dendritic computation: elements of spike processing and neural computation, synaptic plasticity and learning algorithms, unsupervised learning and spike time-dependent plasticity, basic dendritic integration. Projects in MATLAB.

**BME E4030x Neutral control engineering**

Prerequisite(s): ELEN E3801. Topics include basic cell biophysics, active conductance and the Hodgkin-Huxley model, simple neuron models, ion channel models and synaptic models, statistical models of spike generation, Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, sensorimotor integration and optimal state estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and somatosensory pathway, neural encoding model: spike triggered average (STA) and spike triggered covariance (STC) analysis, neuronal response to electrical micro-stimulation, DBS for Parkinson’s disease treatment, motor neural prostheses, and sensory neural prostheses.

**ECBM E4040x or y Neural networks and deep learning**

3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): BMEB W4020 or BMEE E4030 or ECBM E4090 or EECS E4750 or COMS W4771 or an equivalent. Developing features and internal representations of the world, artificial neural networks, classifying handwritten digits with equivalent. Introduction to the statistical mechanics and thermodynamics of biological systems, as well as discussion of bioethics and case studies.

**ECBM E4070y Computing with brain circuits of model organisms**

3 pts. Lect: 3. Professor Lazar.

**ECBM E4090x or y Brain computer interfaces (BCI) laboratory**

3 pts. Lect: 2. Lab: 3. Professor Mesgarani.

**BMEN E4100 BiMeE—Biomedical device design & fabrication**

3 pts. Lect: 3. Professor Kyle.
Prerequisite(s): Instructor’s permission. Human memory, including working, episodic, and procedural memory. Electrophysiology of cognition, noninvasive and invasive recordings. Neural basis of spatial navigation, with links to spatial and episodic memory. Computational models of memory, brain stimulation, lesion studies.

**BMEN E4050x or y Electrophysiology of human memory and navigation**

3 pts. Lect: 3. Professor Jacobs.
Prerequisite(s): Instructor's permission. Human memory, including working, episodic, and procedural memory. Electrophysiology of cognition, noninvasive and invasive recordings. Neural basis of spatial navigation, with links to spatial and episodic memory. Computational models of memory, brain stimulation, lesion studies.

**BMEN E4103x Anatomy of the thorax and abdomen**

Prerequisite(s): Graduate standing in Biomedical Engineering. Designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to their doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4104).

**BMEN E4106x Anatomy laboratory: extremities**

Prerequisite(s): Graduate standing in Biomedical Engineering. Designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to their doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4108).

**BMEN E4108x Anatomy laboratory: head and neck**

Prerequisite(s): Graduate standing in Biomedical Engineering. Corequisite(s): BMEN E4107.

**BMEN E4110x Biostatistics for engineers**

Prerequisite(s): MATH UN1202 or AMPS E2000 and AMPS E2101. Fundamental concepts of probability and statistics applied to biology and medicine. Probability distributions, hypothesis testing and inference, summarizing data and testing for trends, Signal detection theory and the receiver operator characteristic. Lectures accompanied by data analysis assignments using MATLAB and R as well as discussion of bioethics and case studies in biomedical.

**BMEN E4150x The cell as a machine**

Prerequisite(s): MATH UN101 or equivalent. Corequisite(s): One semester of BIOL UN2005 or BIOL UN3501, and one semester of PHYS UN401 or equivalent. Cells as complex micrometer-sized machines, basic physical aspects of cell components (diffusion, mechanics, electrostatics, hydrophobicity), energy transduction (motors, transporters, chaperones, synthesis complexes), basic cell functions. Biophysical principles, feedback controls for robust cell function, adaptation to environmental perturbations.

**BMEN E4210y Driving forces of biological systems**

4 pts. Lect: 4. Professor Sia.
Prerequisite(s): CHEM UN1040 and MATH UN1202 or AMPS E2000. Corequisite(s): BIOL UN2005 or equivalent. Introduction to the statistical mechanics and thermodynamics of biological systems, with a focus on connecting microscopic molecular properties to macroscopic states. Both classical and statistical thermodynamics will be applied to biological systems; phase equilibria, chemical reactions, and colligative properties. Topics in modern biology, macromolecular behavior in solutions and interfaces, protein-ligand binding, and the hydrophobic effect.
BMEN E4303x Structure, mechanics, and adaptation of bone
Introduction to structure, physiology, and biomechanics of bone. Structure, function, and physiology of skeletal bones; linear elastic properties of cortical and trabecular bone; anisotropy and constitutive models of bone tissue; failure and damage mechanics of bone; bone adaptation and fracture healing; experimental determination of bone properties; and morphological analysis of bone microstructure.

BMEN E4302x Biomechanics of musculoskeletal soft tissues
3 pts. Lect: 3. TBA.
Prerequisite(s): ENME E3113 or equivalent.
Restricted to seniors and graduate students.
Biomechanics of orthopaedic soft tissues (cartilage, tendon, ligament, meniscus, etc.). Basic and advanced viscoelasticity applied to the musculoskeletal system. Topics include mechanical properties, applied viscoelasticity theory, and biology of orthopaedic soft tissues.

BMEN E4305y Cardiac mechanics
Prerequisite(s): BMEN E310 and BMEN E4320 or equivalents.
Cardiac anatomy, passive myocardial constitutive properties, electrical activation, ventricular pump function, ventricular-vascular coupling, invasive and noninvasive measures of regional and global function, models for predicting ventricular wall stress. Alterations in muscle properties and ventricular function resulting from myocardial infarction, heart failure, and left ventricular assist.

BMEN E4310x or y Solid biomechanics
3 pts. Lect: 3. Professor Guo.
Prerequisite(s): ENME E3105 and ENME E3113.
Applications of continuum mechanics to the understanding of various biological tissues properties. The structure, function, and mechanical properties of various tissues in biological systems, such as blood vessels, muscle, skin, brain tissue, bone, tendon, cartilage, ligaments, etc., are examined. The establishment of basic governing mechanical principles and constitutive relations for each tissue. Experimental determination of various tissue properties. Medical and clinical implications of tissue mechanical behavior.

BMEN E4320x or y Fluid biomechanics
3 pts. Lect: 3. Professor Guo.
Prerequisite(s): APMA E2101, ENME E3105, and MECE E4100.
The principles of continuum mechanics as applied to biological fluid flows and transport. Continuum formulations of basic conservation laws, Navier-Stokes equations, mechanics of arterial and venous blood flow, blood rheology and non-Newtonian properties, flow and transport in the microcirculation, oxygen diffusion, capillary filtration.

BMEN E4340x Biomechanics of cells
Prerequisite(s): BMEN E320 and BMEN E4300 or equivalents. Survey of experiments and theoretical analyses of the mechanical behavior of individual living nonmuscle cells. Emphasis on quantitative analytic description using continuum mechanics and molecular level theory from the standpoint of statistical mechanics and mechanical models. Mechanics of erythrocytes, leukocytes, endothelial cells, and fibroblasts; models of aggregation, adhesion, locomotion, amoeba motility, cell division and morphogenesis; molecular level models of actin, myosin, microtubules, and intermediate filaments and relation to mechanical properties of cells and cytoskeleton. Alternative models of cytoskeletal mechanics, foam theory, tensegrity. Analysis of experimental techniques including micropipette studies, optical and magnetic cytometry, and nanoindentation.

BMEN E4350y Biomechanics of developmental biology
3 pts. Lect: 3. Professor Nerurkar.
Prerequisite(s): Undergraduate-level course in mechanics (e.g. MECE E3113, BMEN E4310) and cell biology (e.g. BIOL UN2005/6) or by instructor’s permission. Biophysical mechanisms of tissue organization during embryonic development: conservation laws, reaction-diffusion, finite elasticity, and fluid mechanics reviewed and applied to topics in developmental biology, from early development to later organogenesis of the central nervous, cardiovascular, musculoskeletal, respiratory, and gastrointestinal systems. Subdivided into modules on patterning (conversion of diffusible cues into cell fates) and morphogenesis (shaping of tissues). Includes lectures, problem sets, reading of primary literature, and a final project.

BMEN E4400x Wavelet applications in biomedical image and signal processing
Prerequisite(s): APMA E2101 or E3101 or equivalent. An introduction to methods of wavelet analysis and processing techniques for the quantification of biomedical images and signals. Topics include frames and overcomplete representations, multiresolution algorithms for denoising and image restoration, multiscale texture segmentation and classification methods for computer aided diagnosis.

BMEN E4410x Ultrasound in diagnostic imaging
3 pts. Lect: 3. Professor Konofagou.
Prerequisite(s): MATH UN1202 or APMA E2000 or equivalent. Fourier analysis. Physics of diagnostic ultrasound and principles of ultrasound imaging instrumentation. Propagation of plane waves in lossless medium; ultrasound propagation through biological tissues; single-element and array transducer design; pulse-echo and Doppler ultrasound instrumentation, performance evaluation of ultrasound imaging systems using tissue-mimicking phantoms, ultrasound tissue characterization; ultrasound nonlinearity and bubble activity; harmonic imaging; acoustic output of ultrasound systems; biological effects of ultrasound.

BMEN E4420y Biomedical signal processing and signal modeling
Prerequisite(s): ELEN E3801 and either APMA E2101 or E3101 or instructor’s permission.
Fundamental concepts of signal processing in linear systems and stochastic processes. Estimation, detection, and filtering methods applied to biomedical signals. Harmonic analysis, autoregressive model, Wiener and Matched filters, linear discriminants, and independent components. Methods are developed to answer concrete questions on specific data sets in modalities such as ECG, EEG, MEG, ultrasound. Lectures accompanied by data analysis assignments using MATLAB.

BMEN E4430x Principles of magnetic resonance imaging
Prerequisite(s): PHYS UN1403 and APMA E2101, or instructor’s permission. Fundamental principles of Magnetic Resonance Imaging (MRI), including the underlying spin physics and mathematics of image formation with an emphasis on the application of MRI to neuroimaging, both anatomical and functional. The course examines both theory and experimental design techniques.

MEBM E4439x Modeling and identification of dynamic systems
3 pts. Lect: 3. Professor Chbat.
Prerequisite(s): APMA E2101, ELEN E3801 or corequisite(s) EEEN E3601, or instructor’s permission. Generalized dynamic system modeling and simulation. Fluid, thermal, mechanical, diffusive, electrical, and hybrid systems are considered. Nonlinear and high order systems. System identification problem and Linear Least Squares method. State-space and noise representation. Kalman Filter. Parameter estimation via prediction-error and subspace approaches. Iterative and bootstrap methods. Fit criteria. Wide applicability: medical, energy, others. MATLAB and Simulink environments.

BMEN E4440y Physiological control systems
3 pts. Lect: 3. Professor Chbat.

BM EN E4450y Dental and craniofacial tissue engineering
Prerequisite(s): MSAE E3103, BMEN E4210, E4501, or equivalent. Principles of dental and craniofacial bioengineering, periodontal tissue engineering: beyond guided tissue regeneration, craniofacial regeneration by stem cells and engineered scaffolds, biomaterials: Engineering approaches in tissue regeneration, bone biology and development: instructive cues for tissue engineers.

BMEN E4460y Deep learning in biomedical imaging
3 pts. Lect: 3. Professor Laine.
Prerequisite(s): MATH UN1202 or APMA E2000 and APMA E2101. Recommended: background in Python programming. Introduction to methods deep learning, with focus on applications to quantitative problems in biomedical imaging and Artificial Intelligence (AI) in medicine. Network models: Deep feedforward networks, convolutional neural networks and recurrent neural networks. Deep autoencoders for denoising. Segmentation and classification of biological tissues and biomarker of disease. Theory and methods lectures will be accompanied with examples from biomedical image including analysis of neurological images of the brain (MRI), CT images of the lung for cancer and COPD, cardiac ultrasound. Programming assignments will use tensorflow/Pytorch and Jupyter Notebook. Examinations and a final project will also be required.

BMEN E4470x Deep learning for biomedical signal processing
3 pts. Lect: 3. Professor Sajda.
Prerequisite(s): MATH UN1202 or APMA E2000 and APMA E2101. Recommended: background in Python programming. Introduction to methods in deep learning, focus on applications to biomedical signals and sequences. Review of traditional methods for analysis of signals and sequences. Temporal convolutional neural networks and recurrent neural networks. Long-short term memory (LSTM) models and deep state-space models. Theory and methods lectures accompanied with examples from biomedical signal and sequence analysis, including analysis of electroencephalogram (EEG), electrocardiogram (ECG/EKG), and genomics. Programming assignments use tensorflow/keras. Exams and final project required.

BMEN E4480x Statistical machine learning for genomics
3 pts. Lect: 3. Professor Azizi.
Prerequisite(s): APMA E2101, MATH UN1202, MATH UN2010. Proficiency in Python/R programming, and background in probability/statistics. Recommended: COMS W4771. Introduction to statistical machine learning methods using applications in genomic data and in particular high-dimensional single-cell data. Concepts of molecular biology relevant to genomic technologies, challenges of high-dimensional genomic data analysis, bioinformatics preprocessing pipelines, dimensionality reduction, unsupervised learning, clustering, probabilistic modeling, hidden Markov models, Gibbs sampling, deep neural networks, gene regulation, Programming assignments and final project will be required.

BMEN E4490x Magnetic resonance spectroscopy: a window to the living brain
Corequisite(s): Quantitative Physiology I or II. Introduction to use of magnetic resonance spectroscopy (MRS) with focus on the brain. Covers all aspects of in vivo MRS from theory to experiment, from data acquisition to derivation of metabolic signatures, and from study design to clinical interpretation. Includes theoretical concepts, hands-on training in MRS data literacy, and direct experimental experience using a 3T MR scanner.

BMCH E4500x or y Biological transport and rate processes
Prerequisite(s): CHEM UN2443, APMA E2101.

BMEN E4501x or y Biomaterials and scaffold design
3 pts. Lect: 3. Professor Lu.
Prerequisite(s): BIOL UN2005, UN2006, BMEN E4001, and E4002. An introduction to the strategies and fundamental bioengineering design criteria in the development of biomaterials and tissue engineered grafts. Materials structural-functional relationships, biocompatibility in terms of material and host responses. Through discussions, readings, and a group design project, students acquire an understanding of cell-material interactions and identify the parameters critical in the design and selection of biomaterials for biomedical applications.

BMEN E4510x or y Tissue engineering
3 pts. Lect: 3. Professor Hung.
Prerequisite(s): BIOL UN2005, UN2006, BMEN E4001, E4002. An introduction to the strategies and fundamental bioengineering design criteria behind the development of cell-based tissue substitutes. Topics include biocompatibility, biological grafts, gene therapy-transfer, and bioreactors.

BMEN E4520x Synthetic biology: principles of genetic circuits
3 pts. Lect: 3. Professor Danino.
Basic principles of synthetic biology and survey of the field. Fundamentals of biological circuits, including circuit design, modern techniques for DNA assembly, quantitative characterization of genetic circuits, and ODE modeling of biological circuits with MATLAB. Knowledge of biology, ordinary differential equations, and MATLAB will be assumed. Intended for advanced undergraduate and graduate students.

BMEN E4530x Drug and gene delivery
3 pts. Lect: 3. Professor Leong.
Prerequisite(s): BMEN E3010. Application of polymers and other materials in drug and gene delivery, with focus on recent advances in field. Basic polymer science, pharmacokinetics, and biomaterials, cell-substrate interactions, drug delivery system fabrication from nanoparticles to microparticles and electrospray fibrous membranes. Applications include cancer therapy, immunotherapy, gene therapy, tissue engineering, and regenerative medicine. Course readings include textbook chapters and journal papers. Homework assignments take form of essay responding to open-ended question. Term paper and 30-minute PowerPoint presentation required at end of semester.

BMEN E4540y Bioelectrochemistry
Prerequisite(s): CHEM UN3079 and UN2443 or equivalent. Application of electrochemical kinetics to interfacial processes occurring in biomedical systems. Basics of electrochemistry, electrochemical instrumentation, and relevant cell and electrophysiology reviewed. Applications to interpretation of excitable and nonexcitable membrane phenomena, with emphasis on heterogeneous mechanistic steps. Examples of therapeutic devices created as a result of bioelectrochemical studies.

BMEN E4550y Micro- and nanostructures in cellular engineering
3 pts. Lect: 3. Professor Kam.
Prerequisite(s): BIOL UN2005 and UN2006 or equivalent. Design, fabrication, and application of micro-/nanostructured systems for cell engineering. Recognition and response of cells to spatial aspects of their extracellular environment. Focus on neural, cardiac, coculture, and stem cell systems. Molecular complexes at the nanoscale.

BMEN E4560y Dynamics of biological membranes
Prerequisite(s): BIOL UN2005, BMEN E4001, or equivalent. The structure and dynamics of biological (cellular) membranes are discussed, with an emphasis on biophysical properties. Topics include membrane composition, fluidity, lipid asymmetry, lipid-protein interactions, membrane turnover, membrane fusion, transport, lipid phase behavior. In the second half of the semester, students will lead discussions of recent journal articles.

BMEN E4570x Science and engineering of body fluids
Prerequisite(s): General chemistry, organic chemistry, and basic calculus. Body fluids as a dilute solution of polyelectrolyte molecules in water. Study of physical behavior as affected by the presence of ions in surrounding environments. The physics of covalent, ionic, and hydrogen bonds are reviewed, in relation to the structure/properties of the body fluid. Selected physiological processes are examined in physical-chemical terms for polymers.

BMEN E4580y Foundations of nanobioscience and nanobiotechnology
3 pts. Lect: 3. Professor Hess.
Prerequisite(s): BIOL UN2005, UN2006, BMEN E4001-E4002 or instructor's permission. Fundamentals of nanobioscience and nanobiotechnology, scientific foundations, engineering principles, current and envisioned applications. Includes discussion of intermolecular forces and bonding, of kinetics and thermodynamics of self-assembly, of nanoscale transport processes arising from actions of biomolecular motors, computation and control in biomolecular systems, and of mitochondrion as an example of nanoscale factory.
BMEN E4590x BioMems: cellular and molecular applications
3 pts. Lect: 3. Professor Sia.
Prerequisite(s): Chemistry, CHEM UN2443, or CHEM UN3545 or equivalent, MATH UN1201 or APMA E2000, BIOL UN2005, and UN2006. Topics include biomicroelectromechanical, microfluidic, and lab-on-a-chip systems in biomedical engineering, with a focus on cellular and molecular applications. Microfabrication techniques, biocompatibility, miniaturization of analytical and diagnostic devices, high-throughput cellular studies, microfabrication for tissue engineering, and in vivo devices.

BMEN E4600y Cellular electricity
Bioelectricity of the cell membrane. Basis of cell resting voltage, voltage changes that lead to the action potential and electrical oscillations used in sensing systems. Laboratory includes building electronic circuits to measure capacitance of artificial membranes and ion pumping in frog skin. Lab required.

APBM E4650x Anatomy for physicists and engineers
Prerequisite(s): Engineering or physics background. A systemic approach to the study of the human body from a medical imaging point of view: skeletal, respiratory, cardiovascular, digestive, and urinary systems, breast and women's issues, head and neck, and central nervous system. Lectures are reinforced by examples from clinical two- and three-dimensional and functional imaging (CT, MRI, PET, SPECT, U/S, etc.).

BMME E4702x Advanced musculoskeletal biomechanics
Advanced analysis and modeling of the musculoskeletal system. Topics include advanced concepts of 3D segmental kinematics, musculoskeletal dynamics, experimental measurements of joint kinematics and anatomy, modeling of muscles and locomotion, multibody joint modeling, introduction to musculoskeletal surgical simulations.

MEBM E4703y Molecular mechanics in biology
3 pts. Lect: 3. Professor Chbat.
Prerequisite(s): ENME E3105, APMA E2101, or instructor's permission. Mechanical understanding of biological structures including proteins, DNA and RNA in cells and tissues. Force response of proteins and DNA, mechanics of membranes, biophysics of molecular motors, mechanics of protein-protein interactions. Introduction to modeling and simulation techniques, and modern biophysical techniques such as single molecule FRET, optical traps, AFM, and superresolution imaging for understanding molecular mechanics and dynamics.

MEBM E4710x or y Morphogenesis: shape and structure in biological materials
Prerequisite(s): Courses in mechanics, thermodynamics, and ordinary differential equations at the undergraduate level or instructor's permission. Introduction to how shape and structure are generated in biological materials using engineering approach emphasizing application of fundamental physical concepts to a diverse set of problems. Mechanisms of pattern formation, self-assembly, and self-organization in biological materials, including intracellular structures, cells, tissues, and developing embryos. Structure, mechanical properties, and dynamic behavior of these materials. Discussion of experimental approaches and modeling. Course uses textbook materials as well as collection of research papers.

BMEN E4738y Transduction and acquisition of biomedical data
Data transduction and acquisition systems used in biomedicine. Assembly of biotransducers and the analog/digital circuitry for acquiring electrocardiogram, electromyogram, and blood pressure signals. Each small group will develop and construct a working data acquisition board, which will be interfaced with a signal generator to elucidate the dynamics of timing constraints during retrieval of biodata. Lab required.

BMEE E4740y Bioinstrumentation
Prerequisite(s): ELEN E1201, COMS W1005. Hands-on experience designing, building, and testing the various components of a benchtop cardiac pacemaker. Design instrumentation to measure biomedical signals as well as to actuate living tissues. Transducers, signal conditioning electronics, data acquisition boards, the Arduino microprocessor, and data acquisition and processing using MATLAB will be covered. Various devices will be discussed throughout the course, with laboratory work focusing on building an emulated version of a cardiac pacemaker.

BMEN E4750y Sound and hearing
Prerequisite(s): PHYS UN1401 and MATH UN1105-MATH UN1106. Introductory acoustics, basics of waves and discrete mechanical systems. The mechanics of hearing—how sound is transmitted through the external and middle ear to the inner ear, and the mechanical processing of sound within the inner ear.

CMBF W476y Computational genomics
3 pts. Lect: 3. Professor Pe'er.
Prerequisite(s): Working knowledge of at least one programming language, and some background in probability and statistics. Computational techniques for analyzing and understanding genomic data, including DNA, RNA, protein and gene expression data. Basic concepts in molecular biology relevant to these analyses. Emphasis on techniques from artificial intelligence and machine learning. String-matching algorithms, dynamic programming, hidden Markov models, expectation-maximization, neural networks, clustering algorithms, support vector machines. Students with life sciences backgrounds who satisfy the prerequisites are encouraged to enroll.

BMCH E4810y Artificial organs
Analysis and design of replacements for the heart, kidneys, and lungs. Specification and realization of structures for artificial organ systems.

BMEN E4840y Functional imaging for the brain
Prerequisite(s): AME E2101, AME E2200, ELEN E3801, or instructor’s permission. Fundamentals of modern medical functional imaging. In-depth exploration of functional magnetic resonance imaging (fMRI), arterial spin labeling (ASL), and position emission tomography (PET). Human brain anatomy, physiology, and neurophysiological bases underlying each functional imaging. Statistical and digital signal processing methods specific for functional image analysis. Final cumulative project requiring coding in MATLAB, Python, R, or C.

BMEN E4894x Biomedical imaging
Covers image formation, methods of analysis, and representation of digital images. Measures of qualitative performance in the context of clinical imaging. Algorithms fundamental to the construction of medical images via methods of computed tomography, magnetic resonance, and ultrasound. Algorithms and methods for the enhancement and quantification of specific features of clinical importance in each of these modalities.

BMEN E4898y Biophotonics
Prerequisite(s): BMEN E4894 Biomedical imaging, PHYS UN1403 Classical and quantum waves, or instructor’s permission. Provides a broad-based introduction into the field of Biophotonics. Fundamental concepts of optical, thermal, and chemical aspects of the light-tissue interactions will be presented. The application of these concepts for medical therapy and diagnostics will be discussed. The course includes theoretical modeling of light-tissue interactions as well as optical medical instrument design and methods of clinical data interpretation.

BMEN E4999x and y Graduate fieldwork
1–2 pts. Professor Hung.
Prerequisite(s): Obtained internship and approval from faculty adviser. BMEN graduate students only. Only for BMEN graduate students who need relevant work experience as part of their program of study. Final reports required. May not be taken for pass/fail credit or audits.

BMEN E6000x and y Graduate special topics in biomedical engineering
3 pts. Lect: 3. Members of the faculty. Current topics in biomedical engineering. Subject matter will vary by year. Instructors may impose prerequisites depending on the topic.

BMEN E6001x Current topics in nanobiotechnology and synthetic biology
3 pts. Lect: 3. Professor Hess.
Targeted toward graduate students; undergraduates may participate with permission of the instructor. Review and critical discussion
BMEN E6003y Computational modeling of physiological systems
3 pts. Lect: 3. TBA.
Prerequisite(s): BMEN E4001 and E4002 or equivalent, and APMA E4200 or equivalent. Advanced computational modeling and quantitative analysis of selected physiological systems from molecules to organs. Selected systems are analyzed in depth with an emphasis on modeling methods and quantitative analysis. Topics may include cell signaling, molecular transport, excitable membranes, respiratory physiology, nerve transmission, circulatory control, auditory signal processing, muscle physiology, data collection and analysis.

BMEN E6005x Biomedical innovation I
3 pts. Lect: 3. TBA.
Master's students only. Project-based design experience for graduate students. Elements of design process, including need identification, concept generation, concept selection, and implementation. Development of design prototype and introduction to entrepreneurship and implementation strategies. Real-world training in biomedical design and innovation.

BMEN E6006y Biomedical innovation II
3 pts. Lect 3. TBA.
Second semester of project-based design experience for graduate students. Elements of design process, with focus on skills development, prototype development and testing, and business planning. Real-world training in biomedical design, innovation, and entrepreneurship.

BMEN E6007y Lab-to-market: commercializing biomedical innovations
3 pts. Lect: 3. TBA.
Introduction to and application of commercialization of biomedical innovations. Topics include needs clarification, stakeholder analysis, market analysis, value proposition, business models, intellectual property, regulatory, and reimbursement. Development of path-to-market strategy and pitch techniques.

EBBM E6020y Methods of computational neuroscience
Prerequisite(s): BMEB W4020. Formal methods in computational neuroscience including methods of signal processing, communications theory, information theory, systems and control, system identification and machine learning. Molecular models of transduction pathways. Robust adaptation and integral feedback. Stimulus representation and groups. Stochastic and dynamical systems models of spike generation. Neural diversity and ensemble encoding. Time encoding machines and neural codes. Stimulus recovery with time decoding machines. MIMO models of neural computation. Synaptic plasticity and learning algorithms. Major project(s) in MATLAB.

BMEE E6030x Neural modeling and neuroengineering
Prerequisite(s): ELEN E3801, and either APMA E2101 or E3101, or equivalent, or instructor’s permission. Engineering perspective on the study of multiple levels of brain organization, from single neurons to cortical modules and systems. Mathematical models of spiking neurons, neural dynamics, neural coding, and biologically-based computational learning. Architectures and learning principles underlying both artificial and biological neural networks. Computational models of cortical processing, with an emphasis on the visual system. Applications of principles in neuroengineering; neural prostheses, neuromorphic systems and biomimetics. Course includes a computer simulation laboratory. Lab required.

ECBM E6070-6079x or y Topics in neuroscience and deep learning
Prerequisite(s): the instructor’s permission. Selected advanced topics in neuroscience and deep learning. Content varies from year to year, and different topics rotate through the course numbers 6070 to 6079.

EEBM E6090-6099x or y Topics in computational neuroscience and neuroengineering
3 pts. Lect: 2. Professor Sajda.
Prerequisite(s): Instructor’s permission. Selected advanced topics in computational neuroscience and neuroengineering. Content varies from year to year, and different topics rotate through the course numbers 6090-6099.

BMEN E6301y Modeling of biological tissues with finite elements
Prerequisite(s): MECE E6422, or ENME E6315, or equivalent. Structure-function relations and linear/nonlinear constitutive models of biological tissues: anisotropic elasticity, viscoelasticity, porous media theories, mechano-electrochemical models, infinitesimal and large deformations. Emphasis on the application and implementation of constitutive models for biological tissues into existing finite element software packages. Model generation from biomedical images by extraction of tissue geometry, inhomogeneity and anisotropy. Element-by-element finite element solver for large-scale image based models of trabecular bone. Implementation of tissue remodeling simulations in finite element models.

BMEN E6400x Analysis and quantification of medical images
Novel methods of mathematical analysis applied to problems in medical imaging. Design requirements for screening protocols, treatment therapies, and surgical planning. Sensitivity and specificity in screening mammography and chest radiographs, computer aided diagnosis systems, surgical planning in orthopaedics, quantitative analysis of cardiac performance, functional magnetic resonance imaging, positron emission tomography, and echocardiography data.

BMEN E6500x Tissue and molecular engineering laboratory
4 pts. Lect: 1. Lab: 4. TBA.
Prerequisite(s): Biology BIOL UN2005 and BIOL UN2006 or permission of instructor. Hands-on experiments in molecular and cellular techniques, including fabrication of living engineered tissues. Covers sterile technique, culture of mammalian cells, microscopy, basic subcloning and gel electrophoresis, creation of cell-seeded scaffolds, and the effects of mechanical loading on the metabolism of living cells or tissues. Theory, background, and practical demonstration for each technique will be presented. Lab required.

BMEN E6505x or y Advanced biomaterials for tissue engineering
3 pts. Lect: 2.5. Lab: 0.5. Professor Lu.
Prerequisite(s): BMEN E4501 or equivalent. Corequisite(s): BMEN E4001 or E4002. Advanced biomaterial selection and biomimetic scaffold design for tissue engineering and regenerative medicine. Formulation of bio-inspired design criteria, scaffold characterization and testing, and applications on forming complex tissues or organogenesis. Laboratory component includes basic scaffold fabrication, characterization and in vitro evaluation of biocompatibility. Group projects target the design of scaffolds for select tissue engineering applications.

BMEN E6510y Stem cell, genome engineering, and regenerative medicine
Prerequisite(s): Biology, Cell Biology, BMEN E4001 or BMEN E4002. General lectures on stem cell biology followed by student presentations and discussion of primary literature. Themes presented include: basic stem cell concepts; basic cell and molecular biological characterization of endogenous stem cell populations; concepts related to reprogramming; directed differentiation of stem cell populations; use of stem cells in disease modeling or tissue replacement/repair; clinical translation of stem cell research.

EEBM E9070y Massively parallel neural computation
3 pts. Lect: 3. Professor Magarani.
Prerequisite(s): BMEB W4020 or permission of instructor. Drosophila connectomics. Detailed description of the fruit fly’s olfactory and vision systems. Parallel processing on GSPs.

BMEN E9100x or y Master’s research
1–6 pts. Members of the faculty.
Candidates for the M.S. degree may conduct an investigation of some problem in biomedical engineering culminating in a thesis describing the results of their work. No more than 6 points may be counted for graduate credit, and this credit is contingent upon the submission of an acceptable thesis.

BMEN E9500x or y Doctoral research
1–6 pts. Members of the faculty.
Doctoral candidates are required to make an original investigation of a problem in biomedical engineering, the results of which are presented in the dissertation.
BMEN E9700x or y Biomedical engineering seminar
0 pts. Sem: 1. Professors Danino, Juchem, and Olson.
All matriculated graduate students are required to attend the seminar as long as they are in residence. No degree credit is granted. The seminar is the principal medium of communication among those with biomedical engineering interests within the University. Guest speakers from other institutions, Columbia faculty, and students within the department who are advanced in their studies frequently offer sessions.

BMEN E9800x or y Doctoral research instruction
3–12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in biomedical engineering must register for 12 points of doctoral research instruction. Registration may not be used to satisfy the minimum residence requirement for the degree.

BMEN E9900x or y Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate in biomedical engineering or applied biology may be required to register for this course in every term after the student’s coursework has been completed and until the dissertation has been accepted.
Chemical engineering is a highly interdisciplinary field, focused on the study and design of chemical systems from the molecular to the process, system, and global scales. Practicing chemical engineers are in charge of the development and production of diverse materials and processes in traditional chemical industries as well as many emerging new areas. Chemical engineers in industry guide the passage of the product from the laboratory to the marketplace, from ideas and prototypes to functioning articles and processes, from theory to reality. Chemical engineering research is broader still, applying the principles of chemical engineering to the study and design of systems in biochemistry or environmental science, energy, advanced materials, and more.

The expertise of chemical engineers is essential to production, marketing, and application in such areas as renewable energy, pharmaceuticals, high-performance materials in the aerospace and automotive industries, biotechnologies, semiconductors in the electronics industry, paints and plastics, synthetic fibers, artificial organs, biocompatible implants and prosthetics and numerous others. Increasingly, chemical engineers are involved in new technologies employing highly novel materials, whose unusual response at the molecular level endows them with unique properties. Examples include environmental technologies, emerging biotechnologies of major medical importance employing DNA- or protein-based chemical sensors, controlled-release drugs, new agricultural products, nanoparticle-based materials, bio-nanoparticle conjugates, and many others.

Driven by this diversity of applications, chemical engineering is perhaps the broadest of all engineering disciplines, drawing upon physics, chemistry, biology, mathematics and data science, and design. Some of the areas under active investigation are protein engineering, fundamentals and engineering of polymers, biopolymers, and other soft materials, colloidal machines, atmospheric chemistry and air quality, fundamentals and applications of electrochemistry for energy storage and manufacturing, multiphase flows, carbon capture and utilization, catalysis, and electrocatalysis, solar fuels, embryogenesis, the engineering and biochemistry of sequencing the human genome, emergent phenomena in complex and dynamical systems, the biophysics of cellular processes in living organisms, and DNA-guided assembly of inorganic and biological nanoscale objects. Diverse experimental approaches are employed, from NMR, to urban field measurements using sensor networks, to synchrotron techniques, and the theoretical work involves analytical mathematical physics, numerical simulations, and data science.

Interested students will have the opportunity to conduct research in these and other areas. The Department of Chemical Engineering at Columbia is committed to a leadership role in research and education in frontier areas of research and technology where progress derives from the conjunction of many different traditional research disciplines. Increasingly, new technologies and fundamental research questions demand this type of interdisciplinary approach.

The undergraduate program provides a chemical engineering degree that is a passport to many careers in directly related industries as diverse as biochemical engineering, environmental management, and pharmaceuticals. The degree is also used by many students as a springboard from which to launch careers in medicine, law, consulting, management, finance, and so on. For those interested in the fundamentals, a career of research and teaching is a natural continuation of their undergraduate studies. Whichever path the student may choose after graduation, the program offers a deep
understanding of the physical and chemical nature of things and provides an insight into an exploding variety of new technologies that are rapidly reshaping the society in which we live.

Facilities for Teaching and Research
The Department of Chemical Engineering provides access to state-of-the-art research instrumentation and computational facilities for its undergraduate and graduate students, postdoctoral associates, and faculty. The recently renovated chemical engineering undergraduate laboratory features equipment including a Waters HPLC system, a SpectraMax spectrophotometer, a rotating disk electrode and potentiostat, a fixed bed adsorption unit, a solar cell/electrolyzer/fuel cell apparatus, flow and temperature control equipment, an IR camera, two PhyMetrix Benchtop Moisture Analyzer units, and 15 computer work stations.

State-of-the-art specialized research equipment are housed within individual faculty laboratories. Shared research laboratory facilities exist in the Columbia Electrochemical Energy Center, the Soft Materials laboratory, and the Columbia Genome Center. Chemical engineering students, faculty, and research staff also have access to shared NMR, MRI, photochemical, spectroscopic, and mass spectrometry facilities in the Department of Chemistry.

UNDERGRADUATE PROGRAM

Chemical Engineering
Graduates of the Chemical Engineering Program achieve success in one or more of the following within a few years of graduation:

1. Careers in industries that require technical expertise in chemical engineering.
2. Leadership positions in industries that require technical expertise in chemical engineering.
3. Graduate-level studies in chemical engineering and related technical or scientific fields (e.g., biomedical or environmental engineering, materials science).
4. Careers outside of engineering that take advantage of an engineering education, such as business, management, finance, law, medicine, or education.
5. A commitment to life-long learning and service within their chosen profession.

Upon graduation, we expect our students to have:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on teams whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Columbia’s program in chemical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET, http://www.abet.org.

The first and sophomore years of study introduce general principles of science and engineering and include a broad range of subjects in the humanities and social sciences. Although the program for all engineering students in these first two years is to some extent similar, there are a few important differences for chemical engineering majors. Those wishing to learn about, or major in, chemical engineering should take the professional elective CHEN E1000 Chemical engineering for humanity in term I, taught by the Chemical Engineering Department. This course provides a broad overview of modern chemical engineering. Those wishing to major in chemical engineering should also take ENGI E1006 Introduction to computing for engineering and applied scientists in term II. Chemical engineering majors receive additional instruction in CHEN E3020 Analysis of chemical engineering problems, and throughout the major core curriculum, on the use of computational methods to solve chemical engineering problems.

The tables on page 80 and 81 spell out the core course requirements, which are split between courses emphasizing engineering science and those emphasizing practical and/or professional aspects of the discipline. Throughout, skills required of practicing engineers are developed (e.g., writing and presentation skills, competency with computers).

The table on page 81 also shows that a significant fraction of the junior-senior program is reserved for electives, both technical and nontechnical. Twenty-one points (7 courses) of technical electives are included in the junior and senior year requirements. Technical electives are science and/or technology based and feature quantitative analysis. Generally, technical electives must be 3000 level or above but there are a few exceptions including: PHYS UN1403, PHYS UN2601, BIOL UN2005, BIOL UN2006, BIOL UN2501, and CHEM UN2444. A full list of approved technical elective courses in each category can be found on the departmental website or obtained from the departmental advisers. The technical electives are subject to the following constraints:

- **1 Thermodynamics Elective:** One technical elective must fall within the category “Thermodynamics electives”: Chemical engineering courses with 50% or more content related to thermodynamics. Examples include: CHAP 4120, CHEN E4650, CHEN E4880.
### CHEMICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

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<thead>
<tr>
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<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATHEMATICS</strong></td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0)</td>
<td>MATH UN2030 (3) ODE or APMA E2101 (3)</td>
</tr>
<tr>
<td><strong>PHYSICS</strong> (three tracks, choose one)</td>
<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>Lab UN1494 (3)</td>
<td></td>
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<tr>
<td></td>
<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td>Lab UN3081 (2)</td>
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<tr>
<td></td>
<td>UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
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<tr>
<td><strong>CHEMISTRY</strong> (three tracks, choose one)</td>
<td>UN1403 (4) and Lab UN1500 (3)</td>
<td>UN1404 (4)</td>
<td>UN2443 (4)</td>
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</tr>
<tr>
<td></td>
<td>UN1604 (4)</td>
<td>UN2046 (4) and Lab UN1507 (3)</td>
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<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
<td>CC1010 (3) either semester</td>
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<tr>
<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
<td>One core humanities elective (3–4 points)</td>
<td>Three core humanities electives (11 points)</td>
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</tr>
<tr>
<td><strong>CHEM. ENG. REQUIREMENT</strong></td>
<td>CHEN E1000 (1) Chemical engineering for humanity</td>
<td>CHEN E2100 (3) Material and energy balances</td>
<td>CHEN E3020 (3) Analysis of chem. eng. problems</td>
<td></td>
</tr>
<tr>
<td><strong>COMPUTER SCIENCE</strong></td>
<td>ENGI E1006 (3)</td>
<td></td>
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<tr>
<td><strong>THE ART OF ENGINEERING</strong></td>
<td>ENGI E1102 (4) either semester</td>
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<tr>
<td><strong>TOTAL POINTS</strong></td>
<td>17</td>
<td>17</td>
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<td>17</td>
</tr>
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</table>

1 Four core humanities electives should be taken as follows: In Semester III, HUMA CC1001 or COCI CC1101 (4) or any initial course in one of the Global Core sequences offered by the College (3–4); in Semester IV, HUMA CC1002 or COCI CC1102 (4) or ASCM UN2002 or the second course in the Global Core sequence elected in Semester III (3–4), also in Semester IV, ECON UN1105 (4) with UN1155 recitation (0) and either HUMA UN1121 or UN1123 (3).

2 Taking the first track in each row and EN1102 in Semester II.

- **1 Transport Elective**: One technical elective must fall within the category “Transport electives”: Chemical engineering courses with 50% or more content related to transport phenomena (fluid mechanics, heat transfer, or mass transfer). Examples include: CHEN E4150, CHEN E4201, CHEN E4600, CHEN E4630.

- **1 Chemical Engineering Elective**: One upper-level technical course with the designator BMCH, CHEN, CHEE, CHAP, or MECH with significant engineering content.

- **2 SEAS Electives outside Chemical Engineering**: Two upper-level technical courses with significant engineering content.

- **2 Advanced Science Electives**: The remaining two technical elective courses must comprise “advanced science” coursework, which includes the natural sciences and certain engineering coursework. At least one of these courses must be taken outside of SEAS (e.g., in a science department at Columbia). Qualifying engineering courses are determined by Chemical Engineering department advisers.

  The junior-senior technical electives provide the opportunity to explore new, interesting areas beyond the core requirements of the degree. Often, students satisfy the technical electives by taking courses from another SEAS department in order to obtain a minor from that department. Alternately, you may wish to take courses in several new areas, or perhaps to explore familiar subjects in greater depth, or you may wish to gain experience in actual laboratory research. Up to 6 points of CHEN E3900: Undergraduate research project may be counted toward the technical elective content. (Note that if more than 3 points of research are pursued, an undergraduate thesis is required.)

The undergraduate concentrations are a way for students to explore a subject area in modern chemical engineering in depth through their selection of technical elective courses. To fulfill a concentration, the student must complete any combination of four courses (12 points total) from the list of suggested courses in that subject.
Concentration areas are: Climate, Environment, and Energy Solutions; Biotechnology and Biopharmaceuticals; Data and Computational Science; and Advanced Materials. More information on courses satisfying the requirements for each concentration can be found on the departmental website.

The program details discussed above apply to undergraduates who are enrolled at Columbia as first-years and declare the chemical engineering major in the sophomore year. However, the chemical engineering program is designed to be readily accessible to participants in any of Columbia’s Combined Plans and to transfer students. In such cases, the guidance of one of the departmental advisers in planning your program is required (contact information for the departmental UG advisers is listed on the department’s website: cheme.columbia.edu).

**Requirements for a Minor in Chemical Engineering**
See page 207.

**GRADUATE PROGRAMS**
The graduate program in chemical engineering, with its large proportion of elective courses and independent research, offers experience in any of the fields of departmental activity mentioned in previous sections. For both chemical engineers and those with undergraduate educations in other related fields such as physics, chemistry, and biochemistry, the Ph.D. program provides the opportunity to become expert in research fields central to modern technology and science.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

**M.S. Degree**
The requirements are (i) the core courses: (i) math core: Mathematical methods in chemical engineering (CHEN E4010), (ii) transport core: Transport phenomena, III (CHEN E4110) or Transport in fluid mixtures (CHEN E4112), (iii) kinetics core: Advanced chemical kinetics (CHEN E4130) or Surface reactions and kinetics (CHEN E4235), and (iv) thermo core: Advanced chemical engineering thermodynamics (CHEN E4130) or Statistical mechanics (CHAP E4120); and (2) 18 points of 4000-level or higher courses, approved by the graduate coordinator or research adviser, of which up to...
6 may be Master’s research (CHEN 9400). Students with undergraduate preparation in physics, chemistry, biochemistry, pharmacy, and related fields may enroll in the scientist-to-engineer (S2E) program that leads to the master’s degree in chemical engineering. This program requires an extra 6 credits associated with two mandatory Essentials classes (CHEN E4001 and E4002) that are used to ease the transition into chemical engineering.

**Doctoral Degrees**

The Ph.D. and D.E.S. degrees have essentially the same requirements. All students in a doctoral program must (1) earn satisfactory grades in the four core courses (CHEN E4010, E4110, E4330, E4130/CHAP E4120); (2) pass a qualifying exam; (3) defend a proposal of research within 12 months of passing the qualifying exam; (4) defend their thesis; and (5) satisfy course requirements beyond the four core courses. For detailed requirements, please consult the departmental office or graduate coordinator. Students with degrees in related fields such as physics, chemistry, biochemistry, and others are encouraged to apply to this highly interdisciplinary program.

**COURSES IN CHEMICAL ENGINEERING**

*Note: Check the department website for the most current course offerings and descriptions.*

**CHEN E1000x Chemical engineering for humanity**

Introduction to the role of Chemical Engineering in addressing grand challenges facing humanity. Address challenges illustrating the important role that Chemical Engineers play in solving societal problems, including those related to climate change, biotechnology and medicine, clean energy, and sustainable manufacturing of chemicals and materials.

**CHEN E2100x Material and energy balances**

3 pts. Lect: 3. Professor Chen.
Prerequisite(s): First-year chemistry and physics, or equivalent. Serves as an introduction to the chemical engineering profession. Students are exposed to concepts used in the analysis of chemical engineering problems. Rigorous analysis of material and energy balances on open and closed systems is emphasized. An introduction to important processes in the chemical and biochemical industries is provided.

**CHEN E3010x Principles of chemical engineering thermodynamics**

3 pts. Lect: 3. Professor Simunovic.
Prerequisite(s): CHEM UN403 or equivalent. Teaches the formal relationships in the physical world, connecting the fundamental principles with the basis of chemical engineering practice. Topics include the first and second laws of thermodynamics, concepts such as energy and entropy, the equations that relate heat to other forms of energy, properties of ideal and real gases, fluids, single and multicomponent systems, phase and chemical equilibria, and the practical implications of these phenomena to systems from the molecular scale to the living world.

**CHEN E3020y Analysis of chemical engineering problems**

3 pts. Lect: 1.5. Lab: 1.5. Professor Urban.
Prerequisite(s): A Python course. Corequisite(s): Ordinary differential equations. Advance chemical-engineering problem-solving skills through computational tools (primarily developed in Excel or Python). Examples include thermodynamics, transport phenomena, and chemical kinetics. Project based, emphasizing data analysis and report writing. Unstructured collaboration with peers is highly encouraged. Requisite numerical methods and Chemical Engineering concepts are introduced.

**CHEN E3110x Principles of transport phenomena**

3 pts. Lect: 3. Professor Boyce.
Prerequisite(s): mechanics, vector calculus, ordinary differential equations. Mechanistic and mathematical description of the engineering fundamentals of heat and mass transport and fluid mechanics based on mass, momentum and energy balances from the molecular to the continuum to the industrial device scale. Problems and applications will focus on energy, biological and chemical systems and processes.

**CHEN E3230y Transport in biological systems**

3 pts. Lect: 3. Professor Marbella.
Prerequisite(s): CHEN E3010. Reaction kinetics, applications to the design of batch and continuous reactors. Multiple reactions, non-isothermal reactors. Analysis and modeling of reactor behavior.

**BMCH E3500y Transport in biological systems**

Prerequisite(s): CHEM UN2443 and MATH UN2030. Corequisite(s): BIOL UN2005. Convective and diffusive movement and reaction of molecules in biological systems. Kinetics of homogeneous and heterogeneous reactions in biological environments. Methods and models of transport across membranes. Convective diffusion with and without chemical reaction. Diffusion in restricted spaces. Irreversible thermodynamic approaches to transport and reaction in biological systems.

**CHEN E3810y Chemical engineering and applied chemistry lab**

3 pts. Lab: 3. Professor Ju.
Prerequisite(s): CHEN E2100, E4230, E4300, or instructor’s permission. Emphasizes active, experiment-based resolution of open-ended problems involving use, design, and optimization of equipment, products, or materials. Under faculty guidance students formulate, carry out, validate, and refine experimental procedures, for present results in oral and written form. Develops analytical, communications, and cooperative problem-solving skills in the context of problems that span from traditional, large scale separations and processing operations to molecular level design of materials or products. Sample projects include scale up of apparatus, process control, chemical separations, microfluidics, surface engineering, molecular sensing, and alternative energy sources. Safety awareness is integrated.

**CHEN E3900x and y Undergraduate research project**

1–6 pts. Members of the faculty.
Candidates for the B.S. degree may conduct an investigation of some problem in chemical engineering or applied chemistry or carry out a special project under the supervision of the staff. Credit for the course is contingent upon the submission of an acceptable thesis or final report. No more than 6 points may be counted toward the satisfaction of the B.S. degree requirements.

**CHEN E3999x, y, or s Undergraduate fieldwork**

1–2 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from adviser. Restricted to CHEN undergraduate students. Provides work experience on chemical engineering in relevant intern or fieldwork experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed internship/study program. A written report describing the experience and how it relates to the chemical engineering core curriculum is required. Employer feedback on student performance and the quality of the report are the basis of the grade. May not be taken for pass/fail or audited. May not be used as a technical or non-technical elective. May be repeated for credit, but no more than 3 points total of CHEN E3999 may be used for degree credit.

**CHEN E4001x Essentials of chemical engineering—A**

3 pts. Lect: 3. Professor Banta.
Prerequisite(s): First-year chemistry and physics, vector calculus, ordinary differential equations, and the instructor’s permission. Part of an accelerated consideration of the essential chemical engineering principles from the undergraduate program, including topics from Mass and Energy balances, Process Control, and Transport I and II. While required for all M.S. students with Scientist to Engineer status, the credits from this course may not be applied toward any chemical engineering degree.

**CHEN E4002x Essentials of chemical engineering—B**

3 pts. Lect: 3. Professor Venkatasubramanian.
Prerequisite(s): First-year chemistry and physics, vector calculus, ordinary differential equations, and the instructor’s permission. Part of an accelerated consideration of the essential chemical engineering principles from the undergraduate program, including topics from Mass and Energy balances, Process Control, and Transport I and II. While required for all M.S. students with Scientist to Engineer status, the credits from this course may not be applied toward any chemical engineering degree.
CHEN E4010x Mathematical methods in chemical engineering
3 pts. Lect: 3. Professor Venkatasubramanian.
Prerequisite(s): CHEN E4230, or equivalent, or instructor’s permission. Mathematical description of chemical engineering problems and the application of selected methods for their solution. General modeling principles, including model hierarchies. Linear and nonlinear ordinary differential equations and their systems, including those with variable coefficients. Partial differential equations in Cartesian and curvilinear coordinates for the solution of chemical engineering problems.

CHEN E4020y Protection of industrial and intellectual property
3 pts. Lect: 3. Professor Spall.
To expose engineers, scientists and technology managers to areas of the law they are most likely to be in contact with during their career. Principles are illustrated with various case studies together with active student participation.

CHEE E4050y Principles of industrial electrochemistry
Prerequisite(s): CHEE E3010 or equivalent. A presentation of the basic principle underlying electrochemical processes. Thermodynamics, electrode kinetics, and ionic mass transport. Examples of industrial and environmental applications illustrated by means of laboratory experiments: electroplating, refining, and winning in aqueous solutions and in molten salts; electrolytic treatment of wastes; primary, secondary, and fuel cells.

APCH E4080x Soft condensed matter
Prerequisite(s): MSAE E3111, CHEE E3010, or equivalent. Course is aimed at senior undergraduate and graduate students. Introduces fundamental ideas, concepts, and approaches in soft condensed matter with emphasis on biomolecular systems. Covers the broad range of molecular, nanoscale, and colloidal phenomena with revealing their mechanisms and physical foundations. The relationship between molecular architecture and interactions and macroscopic behavior are discussed for the broad range of soft and biological matter systems, from surfactants and liquid crystals to polymers, nanoparticles, and biomolecules. Modern characterization methods for soft materials, including X-ray scattering, molecular force probing, and electron microscopy are reviewed. Example problems, drawn from the recent scientific literature, link the studied materials to the actively developed research areas. Course grade based on midterm and final exams, weekly homework assignments, and final individual/team project.

CHEN E4110y Mechanisms of transport phenomena in fluids
3 pts. Lect: 3. Professor Durning.
Prerequisite(s): CHEN E3110 or equivalent. Continuum framework for modeling non-equilibrium phenomena in fluids with clear connections to molecular/microscopic mechanisms for "conductive" transport. Continuum balances of mass and momentum; continuum-level development of conductive momentum flux (stress tensor) for simple fluids; applications of continuum framework for simple fluids (lubrication flows, creeping flows). Microscopic developments of stress for simple and complex fluids; kinetic theory and/or liquid state models for transport coefficients in simple fluids; Langevin/Fokker-Plank/Smoluchowski framework for stress in complex fluids; stress in active matter; applications for complex fluids.

CHEN E4112y Transport phenomena in fluids and mixtures
3 pts. Lect: 3. Professor Durning.
Prerequisite(s): CHEE E3010 and CHEN E3110 or equivalent. Develops and applies nonequilibrium thermodynamics for modeling of transport phenomena in fluids and their mixtures. Continuum balances of mass, energy, and momentum for pure fluids; nonequilibrium thermodynamic development of Newton’s law of viscosity and Fourier’s law; applications (conduction dominated energy transport, forced and free convection energy transport in fluids); balance laws for fluid mixtures; nonequilibrium thermodynamic development of Fick’s law; applications (diffusion-reaction problems, analogy between energy and mass transport process, transport in electrolyte solutions, sedimentation).

CHEN E4115y Topics in transport phenomena
3 pts. Instructor to be announced.
Prerequisite(s): Undergraduate fluid mechanics, or transport phenomena, or instructor’s permission. Self-contained treatments of selected topics in transport phenomena (e.g., rheology, nonequilibrium thermodynamics, molecular-level aspects of transport turbulence). Topics and instructor may change from year to year. Intended for junior/senior level undergraduates and graduate students in engineering and the physical sciences.

CHAP E4120y Statistical mechanics
3 pts. Lect: 3. Professor O’Shaugnessy.
Prerequisite(s): CHEE E3010 or equivalent. Thermodynamics course, or instructor’s permission. Boltzmann’s entropy hypothesis and its restatement in terms of Helmholtz and Gibbs free energies and for open systems. Correlation times and lengths. Exploration of phase space and observation timescale. Correlation functions. Fermi-Dirac and Bose-Einstein statistics. Fluctuation-response theory. Applications to ideal gases, interfaces, liquid crystals, microemulsions and other complex fluids, polymers, Coulomb gas, interactions between charged polymers and charged interfaces, ordering transitions.

CHEN E4130x Advanced chemical engineering thermodynamics
3 pts. Lect: 3. Professor O’Shaugnessy.
Prerequisite(s): Successful completion of an undergraduate thermodynamics course. The course provides a rigorous and advanced foundation in chemical engineering thermodynamics suitable for chemical engineering Ph.D. students expected to undertake diverse research projects. Topics include intermolecular interactions, nonideal systems, mixtures, phase equilibria and phase transitions and interfacial thermodynamics.

CHEN E4140x Engineering separations
3 pts. Lect: 3. Professor Bishop.
Prerequisite(s): CHEE E2100, E3110, and CHEE E3010 or instructor’s permission. Design and analysis of unit operations employed in chemical engineering separations. Fundamental aspects of single and multistaged operations using both equilibrium and rate-based methods. Examples include distillation, absorption and stripping, extraction, membranes, crystallization, bioseparations, and environmental applications.

CHEN E4150y Computational fluid dynamics in chemical engineering
3 pts. Lect: 3. Professor Boyce.
Fundamentals of numerical algorithms for modeling dynamics of fluid flow computationally. Includes various approaches to discretize time and space on structured and unstructured grids with a variety of boundary conditions. Involves programming of basic CFD codes in MATLAB or Python to test example problems in fluid mechanics with different discretization schemes. Uses open-source software OpenFOAM to investigate more complex geometries and numerical approaches. Introduction to simulation of multiphase flow. Course grade based on homework assignments and final project report and presentation.

CHEN E4201x Engineering applications of electrochemistry
3 pts. Lect: 3. Professor West.
Prerequisite(s): Physical chemistry and a course in transport phenomena. Engineering analysis of electrochemical systems, including electrode kinetics, transport phenomena, mathematical modeling, and thermodynamics. Common experimental methods are discussed. Examples from common applications in energy conversion and metallization are presented.

CHEN E4231x Solar fuels
3 pts. Lect: 3. Professor Esposito.
Prerequisite(s): Graduate standing or CHEN E4230. Fundamentals and applications of solar energy conversion, especially technologies for conversion of sunlight into storable chemical energy or solar fuels. Topics include fundamentals of photoelectrochemistry, kinetics of solar fuels production, solar harvesting technologies, solar reactors, and solar thermal production of solar fuels. Applications include solar fuels technology for grid-scale energy storage, chemical industry, manufacturing, environmental remediation.
CHEN E4235x Surface reactions and kinetics
3 pts. Lect: 3. Professor Chen.
Fundamental concepts and techniques to describe electronic, structural, chemical, and catalytic properties of surfaces. Kinetics and thermodynamics in adsorption, reaction, desorption, and diffusion processes on surfaces. Effects of transport in modifying surface reaction kinetics. Applies basic concepts in the chemical engineering curriculum (mathematical modeling, reaction kinetics, thermodynamics, transport) to surface reactions.

CHEE E4252x Introduction to surface and colloid chemistry
Prerequisite(s): Elemental physical chemistry. The principles of surfaces and colloid chemistry critical to range of technologies indispensable to modern life. Surface and colloid chemistry has significance to life sciences, pharmaceuticals, agriculture, environmental remediation and waste management, earth resources recovery, electronics, advanced materials, enhanced oil recovery, and emerging extraterrestrial mining. Topics include: thermodynamics of surfaces, properties of surfactant solutions and surface films, electrophoretic phenomena at interfaces, principles of adsorption and mass transfer and modern experimental techniques. Leads to deeper understanding of interfacial engineering, particulate dispersions, emulsions, foams, aerosols, polymers in solution, and soft matter topics.

CHEN E4300x Chemical process control and process safety
Prerequisite(s): Material and energy balances. Ordinary differential equations including Laplace transforms. Reactor Design. An introduction to process control applied to chemical engineering through lecture and laboratory. Concepts include the dynamic behavior of chemical engineering systems, feedback control, controller tuning, and process stability. Introduction to the fundamentals of process safety and hazard analysis.

CHEN E4320y Molecular phenomena in chemical engineering
Prerequisite(s): CHEE E3010 or instructor’s permission. Introduces a molecular-level understanding of topics in modern chemical engineering. It builds upon and validates the concepts presented in the rest of the chemical engineering curriculum via a molecular perspective.

CHBM E4321x The genome and the cell
Prerequisite(s): BIOL UN2005, MATH UN2030. The utility of genomic information lies in its capacity to predict the behavior of living cells in physiological, developmental, and pathological situations. The effect of variations in genome structure between individuals within a species, including those deemed healthy or diseased, and among species, can be inferred statistically by comparisons of sequences with behaviors, and mechanistically, by studying the action of molecules whose structure is encoded within the genome. Examines known mechanisms that elucidate the combined effect of environmental stimulation and genetic makeup on the behavior of cells in homeostasis, disease states, and during development, and includes assessments of the probable effect of these behaviors on the whole organism. Quantitative models of gene translation and intracellular signal transduction will be used to illustrate switching of intracellular processes, transient and permanent gene activation, and cell commitment, permanent and death.

CHEN E4325y Bioseparations
3 pts. Lect: 3. Professor Hartounian.
Prerequisite(s): CHEE E2100 or CHEN E3230, or equivalent. Design and analysis of the concentration, recovery, and isolation of biological molecules relevant in biotechnology. The unit operations used in recovery and purification of biological molecules. Theory and design of filtration, microfiltration, centrifugation, cell disruption, extraction, adsorption, chromatography, precipitations, ultrafiltration, crystallization, and drying. Students will have an understanding of basic principles of downstream processing, design and operations of various unit operations used in recovery of biological products, examining traditional unit operations, as well as new concepts and emerging technologies that are likely to benefit biochemical product recovery in the future.

CHEN E4330y Advanced chemical kinetics
3 pts. Lect: 3. Professor Esposito.
Prerequisite(s): CHEE E4230 or instructor’s permission. Complex reactive systems, molecular view of reaction kinetics, reactions in liquid, reactions at surfaces, diffusion-reaction systems. Applications to the design of batch and continuous reactors.

CHEN E4400x Chemical process development
3 pts. Lect: 3. Professor Mottas.
Prerequisite(s): CHEM UN2443 or equivalent or instructor’s permission. Process development for new compounds, including fine and specialty chemicals, pharmaceuticals, biologicals, and agrochemicals. Experimental strategy and methods for process scale-up from bench to pilot plant. Evaluation of process economics. Hazard and risk evaluation for environmental and industrial hygiene safety. Capture and use of process know-how for process and plant design, regulatory approvals, and technology transfer to first manufacture.

CHEN E4500x Process and product design, I
Prerequisite(s): CHEE E4500 or equivalent. The theory of electrochemical corrosion, corrosion tendency, rates, and passivity. Application to various environments. Cathodic protection and coatings. Corrosion testing.

CHEN E4510y Process and product design, II
Prerequisite(s): CHEE E4500 or equivalent. The provisional application of chemical engineering principles to the design and economic evaluation of chemical processes and plants. Use of ASPEN Plus for complex material and energy balances of real processes. Students are expected to build on previous coursework to identify creative solutions to two design projects of increasing complexity. Each design project culminates in an oral presentation, and in the case of the second project, a written report.

CHEN E4550y Chemical process engineering
3 pts. Lect.: 3. Professor Bozic.
Aimed at seniors and graduate students. Provides classroom experience on chemical engineering process safety as well as Safety in Chemical Engineering certification. Process safety and process control emphasized. Application of basic chemical engineering concepts to chemical reactant hazards, industrial hygiene, risk assessment, inherently safer design, hazard operability analysis, and engineering ethics. Application of safety to full spectrum of chemical engineering operations.

CHEN E4570x Artificial intelligence in Chemical Engineering
3 pts. Lect: 3. Professor Venkatasubramanian.
Prerequisite(s): Background in chemical engineering and Python/MATLAB. Introduction to AI methods including knowledge-based systems and deep learning in the context of chemical engineering applications. Topics include chemical engineering modeling approaches, knowledge representation, symbolic reasoning and inference, knowledge-based systems, statistical data analysis, and machine learning methods such as clustering, neural networks, random forests, Bayesian networks, and directed evolution. Chemical engineering case studies in process monitoring, diagnosis, and control, process/product design, scheduling, and process hazards analysis. Development of hybrid models that combine first-principles knowledge of the underlying physics and chemistry with data-driven techniques and the development of causal mechanism-based models.

CHEN E4600y Aerosols
Prerequisite(s): CHEE E4230 or instructor’s per-
mission. Aerosol impacts on indoor and outdoor air quality, health, and climate. Major topics include aerosol sources, physics, and chemistry; field and laboratory techniques for aerosol characterization; aerosol direct and indirect effects on climate; aerosols in biogeochemical cycles and climate engineering; health impacts, including exposure to ambient aerosols and transmission of respiratory disease.

CHEN E4610y Chemical product design
3 pts. Lect: 3. Professor Obermeyer.
Prerequisite(s): CHEE E3010 and CHEM UN2443 or equivalent, or instructor’s permission. Application of chemical and engineering knowledge to the design of new chemical products. Relationships between composition and physical properties. Strategies for achieving desired volumetric, rheological, phase equilibrium, thermal, and environmental behavior. Case studies, including separation solvents, blood substitutes, refrigerants, and aircraft deicing fluids.

CHEN E4620y Introduction to polymers and soft materials
Prerequisite(s): An elementary course in physical chemistry or thermodynamics. Organic chemistry, statistics, calculus and mechanics are helpful, but not essential. An introduction to the chemistry and physics of soft material systems (polymers, colloids, organized surfactant systems and others), emphasizing the connection between microscopic structure and macroscopic physical properties. To develop an understanding of each system, illustrative experimental studies are discussed along with basic theoretical treatments. High molecular weight organic polymers are discussed first (basic notions, synthesis, properties of single polymer molecules, polymer solution and blend thermodynamics, rubber and gels). Colloidal systems are treated next (dominant forces in colloidal systems, flocculation, preparation and manipulation of colloidal systems) followed by a discussion of self-organizing surfactant systems (architecture of surfactants, micelles and surfactant membranes, phase behavior).

CHEN E4630y Topics in soft materials
3 pts. Instructor to be announced.
Prerequisite(s): Physical chemistry or instructor’s permission. Self-contained treatments of selected topics in soft materials (e.g., polymers, colloids, amphiphiles, liquid crystals, glasses, powders). Topics and instructor may change from year to year. Intended for junior/senior level undergraduates and graduate students in engineering and the physical sciences.

CHEN E4650y Polymer physics
3 pts. Lect: 3. Professor Kumar.
Prerequisite(s): CHEN E3110 and E4620. Senior undergraduate/first-year graduate course on the physics of polymer systems. Topics include scaling behavior of chains under different conditions, mixing thermodynamics, networks and generation, polymer dynamics, including reptation and entanglements. Special topics: nanocomposites.

CHEN E4660y Biochemical engineering
3 pts. Lect: 3. Professor Obermeyer.
Prerequisite(s): CHEN E4320 or instructor’s permission. Engineering of biochemical and microbiological reaction systems. Kinetics, reactor design, and design of batch and continuous fermentation and enzyme processes. Recovery and separations in biochemical engineering systems.

CHEN E4670x Chemical engineering data analysis
3 pts. Lect: 3. Professor Bishop.
Prerequisite(s): CHEN E4230 or instructor’s permission. Course is aimed at senior undergraduate and graduate students. Introduces fundamental concepts of Bayesian data analysis as applied to chemical engineering problems. Covers basic elements of probability theory, parameter estimation, model selection, and experimental design. Advanced topics such as nonparametric estimation and Markov chain Monte Carlo (MCMC) techniques are introduced. Example problems and case studies drawn from chemical engineering practice are used to highlight the practical relevance of the material. Theory reduced to practice through programming in Mathematica. Course grade based on midterm and final exams, biweekly homework assignments, and final team project.

CHOR E4690y Managing systemic risk in complex systems
3 pts. Lect: 3. Professor Venkatasubramonian.
Prerequisite(s): Senior or graduate standing in SEAS or instructor’s permission. Course will introduce systems engineering concepts and tools such as digraphs, fault trees, probabilistic risk assessment, HAZOP, FMEA, etc., for modeling enterprise-wide risk in complex systems. Important industrial accidents will be discussed as case studies.

CHEN E4700x Principles of genomic technologies
3 pts. Lect: 3. Professor Ju.

CHEN E4740x Biological transport and rate phenomena, II
Prerequisite(s): Any two of the following: CHEN E3110; BIOL UN2005; or BMCH E3500. Analysis of transport and rate phenomena in biological systems and in the design of biomimetic transport-reaction systems for technological and therapeutic applications. Modeling of homogeneous and heterogeneous biochemical reactions. The Bases of biological transport: roles of convection, ordinary diffusion, forced diffusion. Systems where reaction and transport interact strongly. Applications to natural and artificial tissue beds, tumor modeling, controlled release, natural and artificial organ function.

CHEN E4760y Genomics sequencing laboratory
Prerequisite(s): Undergraduate level biology, organic chemistry, and instructor’s permission. The chemical, biological and engineering principles involved in the genomics sequencing process will be illustrated throughout the course for engineering students to develop the hands-on skills in conducting genomics research.

CHEN E4780x or y Quantitative methods in cell biology
3 pts. Lect: 3. Professor O’Shaughnessy.
Prerequisite(s): Elementary calculus, physics and biology, or instructor’s permission. Quantitative statistical analysis and mathematical modeling in cell biology for an audience with diverse backgrounds. The course presents quantitative methods needed to analyze complex cell biological experimental data and to interpret the analysis in terms of the underlying cellular mechanisms. Optimal and electrical experimental methods to study cells and basic image analysis techniques are described. Methods of statistical analysis of experimental data and techniques to test and compare mathematical models against measured statistical properties will be introduced. Concepts and techniques of mathematical modeling will be illustrated by applications to mechanosensing in cells, the mechanics of cytokinesis during cell division and synaptic transmission in the nervous system. Image analysis, statistical analysis, and model assessment will be illustrated for these systems.

CHEN E4800x Protein engineering
3 pts. Lect: 3. Professor Banta.
Prerequisite(s): CHEN E4230, may be taken concurrently, or the instructor’s permission. Fundamental tools and techniques currently used to engineer protein molecules. Methods used to analyze the impact of these alterations on different protein functions with specific emphasis on enzymatic catalysis. Case studies reinforce concepts covered, and demonstrate the wide impact of protein engineering research. Application of basic concepts in the chemical engineering curriculum (reaction kinetics, mathematical modeling, thermodynamics) to specific approaches utilized in protein engineering.

CHEN E4850x or y Contaminated site cleanup
3 pts. Lect: 3. Professor Tsiamis.
Aimed at senior undergraduate and graduate students. Introduces the science fundamentals and the policies and regulations that govern the cleanup of sites contaminated with hazardous materials and discusses the processes used for their treatment and safe disposal. Covers the methods used to investigate the extent of contamination in soil, groundwater, and sediment.
Uses case studies to illustrate the application of technologies used to address different categories of contaminants (metals, volatile and semivolatile organics). Applies basic concepts in the chemical engineering curriculum to specific approaches utilized in characterizing the fate and transport of contaminants and for designing the engineering processes utilized for their treatment.

CHEN E4860x NMR for bio, soft, and energy materials
3 pts. Lect: 3. Professor Marbella.
Prerequisite(s): PHYS UN1401, CHEE E3010, or instructor's permission. Note: junior/senior undergraduates and graduate (M.S.) students only. Course focuses on the fundamentals of nuclear magnetic resonance (NMR) spectroscopy and imaging in fields ranging from biomedical engineering to electrochemical energy storage. Covers basic NMR theory, instrumentation (including in situ/operando setup), data interpretation, and experimental design to couple with other materials characterization strategies. Course grade based on problem sets, quizzes, and final project presentation.

CHEN E4870y Synthetic organogenesis
3 pts. Lect: 3. Professor Simunovic.
Prerequisite(s): Any quantitative undergraduate course with elements of biology, such as Chemistry, Biochemical Engineering/Biochemistry, Biophysics, or at the instructor's permission. Synthetic organogenesis to use stem cells to reconstitute aspects of embryo development and organ formation in vitro. Examines the molecular basis of human embryogenesis. Introduces synthetic organogenesis as an interdisciplinary field. Students learn to recognize generic molecular mechanisms behind signaling and cell lineage specification. Covers recent advances in applying engineering and contemporary biology to creating organoids and organs on chips using human stem cells.

CHEN E4880x or y Atomistic simulations for science and engineering
Prerequisite(s): statistical mechanics or thermodynamics or instructor's permission. Aimed at senior undergraduates and graduate students. Covers atomistic simulation techniques for applications at interface of chemical engineering and materials science. Theoretical background of various simulation techniques ranging from empirical to first-principles approaches and hands-on experience in using state-of-the-art (free and open source) simulation software. Practical examples focus on inorganic materials mostly in crystalline solids, though methods taught are transferable to other materials classes. Course grades based on reports for practical assignments.

CHEN E4890x or y Biopharmaceuticals, entrepreneurship, and chemical engineering
3 pts. Lect: 3. Professor Hartounian.
Aimed at graduate students of Chemical Engineering. Examines the application of Chemical Engineering fundamentals and entrepreneurship in starting up a biopharmaceutical company and in developing a biopharmaceutical product. Serves as a description of the major stages of developing a biopharmaceutical product. Topics presented will include drug discovery, preclinical and clinical development, IP, manufacturing, and regulatory process. In addition, implementation of the lean startup methodology, business valuation, and financial considerations for a biopharmaceutical startup will be offered. Basic topics in the chemical engineering curriculum (reaction kinetics, mathematical modeling, unit operations, thermodynamics), as well as specific topics in developing biopharmaceuticals will be discussed in this course.

CHEN E4900x or y Topics in chemical engineering
3 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Additional current topics in chemical engineering taught by regular or visiting faculty. Special topics arranged as the need and availability arise. Topics usually offered on a one-time basis. Since the content of this course changes each time it is offered, it may be repeated for credit.

CHEN E4910x and y Solid state chemistry in pharmaceutical development
Prerequisite(s): Thermodynamics (any) or General Chemistry. Fundamentals of solid state as related to pharmaceutical development, and is intended for junior and senior undergraduates and graduate students. Theoretical and practical aspects are covered, including segments on thermal and spectroscopic analytical instrumentation. Topics include crystal structure, polymorphism, crystalization processes, pharmaceutical properties, amorphous solids, solid state reactions, stability testing, solid oral formulation, particle size control, and dissolution testing. Connections between molecular structure, physical structure (e.g., particle size distribution), and product performance will be focus of class.

CHEN E4920x and y Pharmaceutical industry for engineers
Prerequisite(s): General Chemistry and Organic Chemistry. Overview of biopharmaceutical design, development, manufacturing, and regulatory requirements from an engineering perspective. Unit operations, equipment selection, and process development associated with small molecule, biologics, and vaccine manufacturing illustrated through examples, and quantitative engineering approaches applied as appropriate. Small molecules, biologics, vaccines, solid oral formulations, sterile processing, and design of experiments (DoE) treated along with a module on regulatory requirements.

CHEN E4930y Biopharmaceutical process laboratory
Prerequisite(s): Organic Chemistry Lab I, Undergraduate organic Chemistry. Laboratory-based course intended for junior and senior undergraduate and graduate students interested in gaining hands-on experience in biopharmaceutical industry, including tabletting, dissolution, disintegration, fermentation, chromatography, tangential flow filtration, mixing, and crystallization. Connections between process parameters, chemical and molecular properties, process parameters, chemical and molecular properties, process performance, and product attributes illustrated through combination of lectures (given during lab time) experiments, and report writing.

CHEN E4999x and y Fieldwork
1.5–3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): M.S. student. Intended only for M.S. students. Provides work experience on chemical engineering in relevant intern or field-work experience as part of their program of study as determined by the instructor. A written report describing their experience and how it relates to the chemical engineering core curriculum is required. Employer feedback on student performance and the quality of the report are the basis of the grade. May not be taken for pass/fail credit or audited. Only 3 points of CHEN E4999 can be credited toward the M.S. degree. Furthermore, students who take CHEN E4999 can use only a maximum of 3 points of CHEN E9400 in fulfillment of the M.S. degree.

CHEN E6050x Advanced electrochemistry
Prerequisite(s): Instructor's permission. An advanced overview of the fundamentals of electrochemistry, with examples taken from modern applications. An emphasis is placed on mass transfer and scaling phenomena. Principles are reinforced through the development of mathematical models of electrochemical systems. Course projects will require computer simulations. The course is intended for advanced graduate students, conducting research involving electrochemical technologies.

EACH E6181x Advanced electrochemical energy storage
3 pts. Lect: 3. Professor Steingart.
Prerequisite(s): EAEE E4180, EAEE E4002. Most modern commercial implementations of electrochemical energy storage are not fully deterministic: provides context and best-hypotheses for modern challenges. Topics include current understanding of Lithium/Lithium Anode Solid-Electrolyte-Interphase, Reversible and Irreversible Side Reactions in Redox flow systems, electrochemically correlated mechanical fracture at multiple scales, relationships between electrolyte solvation and electrode insertion, roughening, smoothing, and detachment behavior of metal anodes, best practices in structural, chemical, and microscopic characterization, morphological vs. macro-homogenous transport models, particle to electrode to cell nonlinearity.

CHEE E6201x or y Topics in electrochemical energy storage and conversion
3 pts. Lect: 3. Professor West.
Prerequisite(s): CHEE E4201 or instructor's permission. Selected topics in electrochemical energy storage and/or conversion. Experimental, theoretical, and technological topics vary. Critical analysis of scientific and engineering literature. Team
projects and student-led discussions. Topics and instructor may change from year to year. Note: recommended for Ph.D. students.

**CHEE E6220y Equilibria and kinetics in hydrometallurgical systems**
3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): Instructor's permission. An advanced overview of the fundamentals of electrochemistry, with examples taken from modern applications. An emphasis is placed on mass transfer and scaling phenomena. Principles are reinforced through the development of mathematical models of electrochemical systems. Course projects will require computer simulations. The course is intended for advanced graduate students, conducting research involving electrochemical technologies.

**CHEE E6252y Applied surface and colloid chemistry**
3 pts. Lect: 2. Lab: 3. Professors Somasundaran and Farinato. Prerequisite(s): CHEE E4252. Applications of surface chemistry principles to wetting, flocculation, flotation, separation techniques, catalysis, mass transfer, emulsions, foams, aerosols, membranes, biological surfactant systems, microbial surfaces, enhanced oil recovery, and pollution problems. Appropriate individual experiments and projects. Lab required.

**CHEN E6543x Chemical engineering research methodology**
1 pts. Professor Bishop. For first year graduate students entering the Ph.D. program. Serves as a "survival skills" course to familiarize students with graduate studies, research, technical writing, and professionalism. Covers manuscript preparation, proposal preparation, protection of intellectual property, professional ethics, etc. Topics include: (1) laboratory safe practices including rules administered by EHRS and preparation for obtaining the required NYFD Certificate of Fitness, (2) expectations and responsibilities of teaching assistants (TAs) and (3) rules, milestones, and assessment of progress within the Chemical Engineering graduate program.

**CHEN E8100y Topics in biology**
3 pts. Lect: 3. Professor O'Shaughnessy. Prerequisite(s): Instructor's permission. This research seminar introduces topics at the forefront of biological research in a format and language accessible to quantitative scientists and engineers lacking biological training. Conceptual and technical frameworks from both biological and physical science disciplines are utilized. The objective is to reveal to graduate students where potential lies to apply techniques from their own disciplines to address pertinent biological questions in their research. Classes entail reading, criticism and group discussion of research papers and textbook materials providing overviews to various biological areas including: evolution, immune system, development and cell specialization, the cytoskeleton and cell motility, DNA transcription in gene circuits, protein networks, recombinant DNA technology, aging, and gene therapy.

**CHEN E9000x and y Chemical engineering colloquium**
0 pts. Col: 1. Professor Esposito. Graduate students on the Ph.D. track are required to attend the department colloquium as long as they are in residence. No degree credit is granted.

**CHEN E901tx M.S. Chemical engineering colloquium**
0 pts. Lect: 1. Professor Bozic. Required for all M.S. students in residence in their first semester. Topics related to professional development and the practice of chemical engineering. No degree credits granted. Intended for M.S. students only.

**CHEN E9400x and y Master’s research**
1–6 pts. Members of the faculty. Prescribed for M.S. and Ch.E. candidates; elective for others with the approval of the Department. Degree candidates are required to conduct an investigation of some problem in chemical engineering or applied chemistry and to submit a thesis describing the results of their work. No more than 6 points may be counted for graduate credit, and this credit is contingent upon the submission of an acceptable thesis.

**CHEN E9500x and y–S9500 Doctoral research**
1–15 pts. Members of the faculty. Prerequisite(s): The qualifying examinations for the doctorate. Open only to certified candidates for the Ph.D. and Eng.Sc.D degrees. Doctoral candidates in chemical engineering are required to make an original investigation of a problem in chemical engineering or applied chemistry, the results of which are presented in their dissertations. No more than 15 points of credit toward the degree may be granted when the dissertation is accepted by the department.

**CHEN E9600x and y Advanced research problems**
2–10 pts. Members of the faculty. Prerequisite(s): Recommendation of the professor concerned and approval of the master’s research department. For postdoctoral students and other qualified special students who wish to pursue research under the guidance of members of the department. Not open to undergraduates or to candidates for the degrees of Ch.E., M.S., Ph.D., or Eng.Sc.D.

**CHEN E9800x and y Doctoral research instruction**
3, 6, 9, or 12 pts. Members of the faculty. A candidate for the Eng.Sc.D. degree in chemical engineering must register for 12 points of doctoral research instruction. Registration in CHEN E9800 may not be used to satisfy the minimum residence requirement for the degree.

**CHEN E9900x and y–S9900 Doctoral dissertation**
0 pts. Members of the faculty. Open only to certified doctoral candidates. A candidate for the doctorate in chemical engineering may be required to register for this course in every term after the student’s coursework has been completed, and until the dissertation has been accepted.
The Department of Civil Engineering and Engineering Mechanics focuses on two broad areas of instruction and research. The first, the classical field of civil engineering, deals with the planning, design, construction, and maintenance of the built environment. This includes buildings, foundations, bridges, transportation facilities, nuclear and conventional power plants, hydraulic structures, and other facilities essential to society. The second is the science of mechanics and its applications to various engineering disciplines. Frequently referred to as applied mechanics, it includes the study of the mechanical and other properties of materials, stress analysis of stationary and movable structures, the dynamics and vibrations of complex structures, aero- and hydrodynamics, and the mechanics of biological systems.

MISSION
The department aims to provide students with a technical foundation anchored in theory together with the breadth needed to follow diverse career paths, whether in the profession via advanced study or apprenticeship, or as a base for other pursuits.

Current Research Activities
Current research activities in the Department of Civil Engineering and Engineering Mechanics are centered in the areas outlined below. A number of these activities impact directly on problems of societal importance, such as rehabilitation of the infrastructure, mitigation of natural or man-made disasters, and environmental concerns.


Multihazard risk assessment and mitigation: integrated risk studies of the civil infrastructure form a multihazard perspective, including earthquake, wind, flooding, fire, blast, and terrorism. The engineering, social, financial, and decision-making perspectives of the problem are examined in an integrated manner.

Probabilistic mechanics: random processes and fields to model uncertain loads and material/soil properties, nonlinear random vibrations, reliability and safety of structural systems, computational stochastic mechanics, stochastic finite element and boundary element techniques, Monte Carlo simulation techniques, random micromechanics.

Structural control and health monitoring: topics of research in this highly cross-disciplinary field include the development of “smart” systems for the mitigation and reduction of structural vibrations, assessment of the health of structural systems based on their vibration response signatures, and the modeling of nonlinear systems based on measured dynamic behavior.

Fluid mechanics: numerical and theoretical study of fluid flow and transport processes, nonequilibrium fluid dynamics and thermodynamics, turbulence and turbulent mixing, boundary-layer flow, urban and vegetation canopy flow, particle-laden flow, wind loading, flow through porous...
media, and flow and transport in fractured rock.

**Environmental engineering/water resources:** modeling of flow and pollutant transport in surface and subsurface waters, unsaturated zone hydrology, geoenvironmental containment systems, analysis of watershed flows including reservoir simulation.

**Structures:** dynamics, stability, and design of structures, structural failure and damage detection, fluid and soil structure interaction, ocean structures subjected to wind-induced waves, inelastic dynamic response of reinforced concrete structures, earthquake-resistant design of structures.

**Geotechnical engineering:** soil behavior, constitutive modeling, reinforced soil structures, geotechnical earthquake engineering, liquefaction and numerical analysis of geotechnical systems.

**Structural materials:** cement-based materials, micro- and macromodels of fiber-reinforced cement composites, utilization of industrial by-products and waste materials, beneficiation of dredged material.

**Earthquake engineering:** response of structures to seismic loading, seismic risk analysis, active and passive control of structures subject to earthquake excitation, seismic analysis of long-span cable-supported bridges.

**Flight structures:** composite materials, smart and multifunctional structures, multiscale and failure analysis, vibration control, computational mechanics and finite element analysis, fluid-structure interaction, aeroelasticity, optimal design, and environmental degradation of structures.

**Advanced materials:** multifunctional engineering materials, advanced energy materials, durable infrastructure materials, new concretes/composites using nanotubes, nanoparticles, and other additives with alternative binders, sustainable manufacturing technologies, rheological characterization for advanced cement/concrete placement processes.

**Computational mechanics:** aimed at understanding and solving problems in science and engineering, topics include multiscale methods in space and time (e.g., homogenization and multigrid methods); multiphysics modeling; material and geometric nonlinearities; strong and weak discontinuities (e.g., cracks and inclusions); discretization techniques (e.g., extended finite element methods and mixed formulations); verification and validation (e.g., error analysis); software development and parallel computing.

**Multiscale mechanics:** solving various engineering problems that have important features at multiple spatial and temporal scales, such as predicting material properties or system behavior based on information from finer scales; focus on information reduction methods that provide balance between computational feasibility and accuracy.

**Transportation engineering:** understanding and modeling transportation systems that are radically evolving due to emerging communication and sensing technologies; leveraging large data collected from various traffic sensors to understand transformation in travel behavior patterns; modeling travel behavior using a game theory approach to help decision-makers understand upcoming changes and prepare for effective planning and management of next generation transportation systems.

**Construction engineering and management:** contracting strategies; alternative project delivery systems; minimizing project delays and disputes; advanced technologies to enhance productivity and efficiency; strategic decisions in global engineering and construction markets; industry trends and challenges.

**Infrastructure delivery and management:** decision support systems for infrastructure asset management; assessing and managing infrastructure assets and systems; capital budgeting processes and decisions; innovative financing methods; procurement strategies and processes; data management practices and systems; indicators of infrastructure performance and service; market analysis.

**Facilities**

The offices and laboratories of the department are in the S. W. Mudd Building and the Engineering Terrace.

**Computing**

The department manages a substantial computing facility of its own in addition to being networked to all the systems operated by the University. The department facility enables its users to perform symbolic and numeric computation, three-dimensional graphics, and expert systems development. Connections to wide-area networks allow the facility’s users to communicate with centers throughout the world. All faculty and student offices and department laboratories are hardwired to the computing facility, which is also accessible remotely to users. Numerous personal computers and graphics terminals exist throughout the department, and a PC lab is available to students in the department in addition to the larger school-wide facility.

**Laboratories**

Robert A. W. Carleton Strength of Materials Laboratory

The Carleton Laboratory serves as the central laboratory for all experimental work performed in the Department of Civil Engineering and Engineering Mechanics. It is the largest laboratory at Columbia University’s Morningside campus and is equipped for teaching and research in all types of engineering materials and structural elements, as well as damage detection, fatigue, vibrations, and sensor networks. The Laboratory has a full-time staff who provide assistance in teaching and research. The Laboratory is equipped with a strong floor that allows for the testing of full-scale structural components such as bridge decks, beams, and columns. Furthermore, it is equipped with universal testing machines ranging in capacity from 150 kN (30,000 lbs.) to 3 MN (600,000 lbs.). The seamless integration of both research and teaching in the same shared space allows civil engineering students of all degree tracks to gain a unique appreciation of modern experimental approaches to material science and engineering mechanics.

The Carleton Laboratory serves as the hub of instruction for classes offered...
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<th>SEMESTER I</th>
<th>SEMESTER II</th>
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<td><strong>MATHEMATICS</strong></td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0)</td>
<td>APMA E2101 (3) intro. to applied math.</td>
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<td>UN1402 (3)</td>
<td>Lab UN1494 (3) or chem. lab</td>
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<td>(three tracks,</td>
<td>UN1601 (3.5)</td>
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<tr>
<td>choose one)</td>
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<tr>
<td><strong>CHEMISTRY</strong></td>
<td>one-semester lecture (3–4): UN1403 or UN1404 or UN2045 or UN1604 Chem lab UN1500 (3) either semester or physics lab</td>
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<tr>
<td><strong>GEOLOGY</strong></td>
<td>EESC UN1011 (4.5), UN2100 (4.5), UN2200 (4.5), UN2300 (4.5), or equivalent</td>
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<td>ENME E3105 (4)</td>
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<tr>
<td><strong>CIVIL ENGINEERING</strong></td>
<td>CIEN E3000 (3)</td>
<td>(Spring semester; recommended but not required)</td>
<td>CIEE E3260 (3) Eng. for comm. dev.</td>
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<td>CC1010 (3) either semester</td>
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<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
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<td>HUMA CC1001, COCI CC1101, or Global Core (3–4)</td>
<td>HUMA CC1002, COCI CC1102, or Global Core (3–4) and ECON UN1105 (4) and UN1155 recitation (0)</td>
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<td></td>
<td>ENGI E1102 (4) either semester</td>
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</table>

by the Department of Civil Engineering and Engineering Mechanics, most prominently ENME E3114 Experimental Mechanics of Materials, ENME E3106 Dynamics and Vibrations, and CIEN E3141 Soil Mechanics. The Laboratory also hosts and advises the AISC Steel Bridge Team in the design, fabrication, and construction phases of their bridge, which goes to regional and national competition annually.

Additionally, the Carleton Laboratory has a fully outfitted machine shop capable of machining parts, fittings, and testing enclosures in steel, nonferrous metals, acrylic, and wood. The Carleton Machine Shop's machine tool pool is state-of-the-art, either of the latest generation or recently rebuilt and modernized. The machine shop is open for use by undergraduate students performing independent research and is supported by the Lab’s senior lab technician.

**The Donald M. Burmister Soil Mechanics Laboratory**

The Burmister Laboratory contains equipment and workspace to carry out all basic soil mechanics testing for our undergraduate and graduate programs. Several unique apparatuses have been acquired or fabricated for advanced soil testing and research: automated plain strain/triaxial apparatus for stress path testing at both drained and undrained conditions, direct shear device for minimum compliance, and a unique sand hopper which prepares foundations and slopes for small scale model testing. The Laboratory has established a link and cooperation for large-scale testing for earthquake and geosynthetic applications with NRIAE, the centrifuge facilities at the Rensselaer Polytechnic Institute and the Tokyo Institute of Technology.

**The Heffner Hydrologic Research Laboratory**

The Heffner Laboratory is a facility for both undergraduate instruction and research in aspects of fluid mechanics, environmental applications, and water resources. The Heffner Laboratory houses the facilities for teaching the laboratory component of the ENME E3161 Fluid Mechanics course and includes multiple hydraulic benches with a full array of experimental modules.
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<tr>
<th></th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
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<td><strong>CORE REQUIRED COURSES</strong></td>
<td>ENME E3113 (3) Mech. of solids</td>
<td>CIEN E3125 (3) Structural design</td>
<td>CIEN E3111 (3.5) Uncertainty and risk in civil infrastructure systems</td>
<td>CIEN E3128 (4) Design projects</td>
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<td>ENME E3161 (4) Fluid mech.</td>
<td>CIEN E3126 (1) Computer-aided struct. design</td>
<td>CIEN E3129 (3) Proj. mgmt. for construction</td>
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<td><strong>GEOTECH ENG. (GE) OR STRUCT. ENG. (SE)</strong></td>
<td>ENME E3106 (3) Dynamics and vibrations</td>
<td>ENME E3114 (4) Exper. mech. of materials</td>
<td>ENME E3332 (3) A first course in finite elements</td>
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<td></td>
<td>CIEN E3121 (3) Struct. analysis</td>
<td>CIEN E3127 (3) Struct. design projects (SE) or CIEN E4241 (3) Geotech. eng. fund. (GE)</td>
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<td>3 points</td>
<td>9 points</td>
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<td><strong>CIVIL ENG. AND CONSTR. MGMT.</strong></td>
<td>ENME E3114 (4) Exper. mech. of materials</td>
<td>CIEN E4133 (3) Capital facility planning and financing</td>
<td>CIEN E3127 (3) Struct. design projects or CIEN E4241 (3) Geotech. eng. fund.</td>
<td>CIEN E4131 (3) Princ. of constr. tech.</td>
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<td></td>
<td>CIEN E3121 (3) Struct. analysis</td>
<td>or CIEE E3250 (3) Hydrosystems eng.</td>
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<td>CIEE E3255 (3) Environ. control / pollution</td>
<td>CIEE E4257 (3) Ground contam. transport / remed.</td>
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<td><strong>WATER RES. / ENVIRON. ENG.</strong></td>
<td>CIEE E3250 (3) Hydrosystems eng.</td>
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<td>CIEN E3303 (1) Independent studies</td>
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## ENGINEERING MECHANICS PROGRAM: FIRST AND SECOND YEARS

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<td>Lab UN3081 (2)</td>
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<td>One-semester lecture (3–4): UN1403 or UN1404 or UN2045 or UN1604 Chem lab UN1500 (3) either semester or physics lab</td>
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<td>ENME E3105 (4) any semester</td>
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<td>TECH ELECTIVES</td>
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<td><strong>COMPUTER</strong></td>
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<td>SCIENCE</td>
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<td>EDUCATION</td>
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<td>UN1002 (1)</td>
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<td><strong>THE ART OF</strong></td>
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<tr>
<td>ENGINEERING**</td>
<td>ENGI E1102 (4) either semester</td>
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### The Eugene Mindlin Laboratory for Structural Deterioration Research
The Mindlin Laboratory has been developed for teaching and research dedicated to all facets of the assessment of structures, deterioration of structural performance and surface coatings, dynamic testing for earthquakes, and other applications. The commissioning of a state-of-the-art 150 kN Instron universal testing machine, a QUV ultraviolet salt spray corrosion system, a freeze-thaw tester, a Keyence optical microscope and surface analyzer have further expanded the Mindlin Laboratory’s capabilities in material testing and characterization. The Mindlin Laboratory also serves as a state-of-the-art medium scale nondestructive structural health monitoring facility, allowing the conduct of research in the assessment of our nation’s degrading civil infrastructure.

### The Institute of Flight Structures
The Institute of Flight Structures was established within the department through a grant by the Daniel and Florence Guggenheim Foundation. It provides a base for graduate training in aerospace and aeronautical related applications of structural analysis and design.

### UNDERGRADUATE PROGRAMS
The Department of Civil Engineering and Engineering Mechanics focuses on two broad areas of instruction and research. The first, the classical field of civil engineering, deals with the planning, design, construction, and maintenance of structures and the infrastructure. These include buildings, foundations, bridges, transportation facilities, nuclear and conventional power plants, hydraulic structures, and other facilities essential to society. The second is the science of mechanics and its applications to various engineering disciplines. Frequently referred to as applied mechanics, it includes the study of the mechanical properties of materials, stress analysis of stationary and movable structures, the dynamics and vibrations of complex structures, aero- and hydrodynamics, micro- and nanomechanics, and the mechanics of biological and energy systems.

### Program Objectives
1. Graduates with a broad and fundamental technical base will be able to enter the professional civil engineering workforce either with a B.S. to
develop specialized expertise by way of apprenticeship or through the increasingly common path of a specialized M.S.

2. Graduates with a firm foundation in the basic math, science, and engineering science that underlie all technological development will be well equipped to adapt to changing technology in the profession.

3. Graduates equipped with a broad technical background will be able to follow other technical or nontechnical career paths.

4. Graduates will practice their profession with effective writing and communication skills, with professional ethics, as well as with awareness of societal issues.

Student Outcomes

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on teams whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Engineering Mechanics

The prerequisites for this program are the courses listed in the First and Second Years Program (see above) or their equivalents. The civil engineering program offers three areas of concentration: civil engineering and construction management, geotechnical engineering or structural engineering, and water resources/environmental engineering. In the junior and senior years, 15 credits of technical electives are allocated.

Columbia’s program in civil engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET, http://www.abet.org.

Minor in Architecture

Civil engineering program students may want to consider a minor in architecture (see page 206).

GRADUATE PROGRAMS

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

Master of Science Degree Program

The Department of Civil Engineering and Engineering Mechanics offers
a graduate program leading to the degree of Master of Science (M.S.) in Civil Engineering and Engineering Mechanics. The Master of Science degree is awarded upon the satisfactory completion of a minimum of 30 points of credit of approved graduate study extending over at least two semesters.

The M.S. program is very flexible and includes minimal core course requirements. Every student is assigned a faculty member as an academic adviser. Student and adviser meet regularly and plan together the sequence of courses that best fit the student's interests. While a suitable M.S. program will necessarily entail some degree of specialization, the program of study established between the student and the adviser should be well balanced, including basic subjects of broad importance as well as theory and applications. Students may take graduate-level courses from across various concentrations within the department and may complete multiple concentrations.

The Master of Science concentrations are:
- Advanced Infrastructure Materials
- Computational and Data-Driven Engineering Mechanics
- Construction Engineering and Management
- Construction Strategic Management, Entrepreneurship, and Leadership
- Engineering Mechanics
- Environmental Engineering and Water Resources
- Forensic (Structural) Engineering
- Geotechnical Engineering
- Infrastructure Engineering
- Real Estate Development, Construction, and Finance
- Smart and Sustainable Cities
- Structural Engineering
- Transportation Engineering

**Doctoral Degree Programs**

Two doctoral degrees in engineering are offered within the department: the Doctor of Engineering science (Eng.Sc.D.), administered by The Fu Foundation School of Engineering and Applied Science, and the Doctor of Philosophy (Ph.D.), administered by the Graduate School of Arts and Science. The Eng.Sc.D. and Ph.D. programs have nearly identical academic requirements with regard to courses, qualifying examinations, and the dissertation, but differ in residence requirements and in certain administrative details. A student must obtain the master's degree (M.S.) before enrolling as a candidate for either the Ph.D. or Eng.Sc.D. degree.

In conjunction with their faculty adviser, doctoral degree students plan an appropriate course of study related to their area of focus within the department. Doctoral degree students must complete a minimum of 30 credits of graduate-level coursework beyond the M.S. degree. Candidates for the Eng. Sc.D. degree must also accumulate 12 credits in the departmental course CIEN 9800 Doctoral Research Instruction. In addition to coursework requirements, doctoral degree students must write a dissertation embodying original research under the sponsorship of their faculty adviser.

Major research thrusts for the doctoral degree programs include:
- Computational mechanics
- Multiscale mechanics
- Poromechanics
- Dynamics and vibrations
- Infrastructure monitoring
- Cementitious materials and concrete
- Advanced infrastructure materials
- Structural safety and reliability
- Probabilistic mechanics
- Sustainable/green infrastructure
- Geomechanics
- Fluid mechanics
- Autonomous transportation
- Disasters and natural hazards

**Civil Engineering**

By selecting technical electives, students may focus on one of several areas of concentration or prepare for future endeavors such as architecture.

**Construction Engineering and Management**: capital facility planning and financing, strategic management, managing engineering and construction processes, construction industry law, construction techniques, managing civil infrastructure systems, civil engineering and construction entrepreneurship.

**Environmental Engineering and Water Resources**: transport of water-borne substances, hydrology, sediment transport, hydrogeology, and geoenvironmental design of containment systems.

**Geotechnical Engineering**: soil mechanics, foundation engineering, earth-retaining structures, slopes, and geotechnical earthquake engineering.

**Forensic (Structural) Engineering**: investigation and determination of the causes of structural failures of buildings, bridges, and other constructed facilities.

**Structural Engineering**: applications to steel and concrete buildings, bridges, and other structures.

**Engineering Mechanics**

Programs in engineering mechanics offer comprehensive training in the principles of applied mathematics and continuum mechanics and in the application of these principles to the solution of engineering problems. The emphasis is on basic principles, enabling students to choose from among a wide range of technical areas. Students may work on problems in such disciplines as systems analysis, acoustics, and stress analysis, and in fields as diverse as transportation, environmental, structural, nuclear, and aerospace engineering. Program areas include:

- **Continuum mechanics**: solid and fluid mechanics, theories of elastic and inelastic behavior, and damage mechanics.
- **Vibrations**: nonlinear and random vibrations; dynamics of continuous media, of structures and rigid bodies, and of combined systems, such as fluid-structure interaction; active, passive, and hybrid control systems for structures under seismic loading; dynamic soil-structure interaction effects on the seismic response of structures.
- **Random processes and reliability**: problems in design against failure under earthquake, wind, and wave loadings; noise, and turbulent flows; analysis of structures with random properties.
- **Fluid mechanics**: turbulent flows, two-phase flows, fluid-structure interaction, fluid-soil interaction, flow in porous media, computational methods for flow and transport processes, and
flow and transport in fractured rock under mechanical loading

- Computational mechanics: finite element and boundary element techniques, symbolic computation, and bioengineering applications.

A flight structures program is designed to meet the needs of industry in the fields of high-speed and space flight. The emphasis is on mechanics, mathematics, fluid dynamics, flight structures, and control. The program is a part of the Guggenheim Institute of Flight Structures in the department. Specific information regarding degree requirements is available in the department office.

**COURSES IN CIVIL ENGINEERING**

See also Courses in Engineering Mechanics at the end of this section.

**CIEN E3000y The art of structural design**
3 pts. Lect: 3. Professor Deodatis.
Basic scientific and engineering principles for the design of buildings, bridges, and other parts of the built infrastructure. Application of principles to analysis and design of actual large-scale structures. Coverage of the history of major structural design innovations and of the engineers who introduced them. Critical examination of the unique aesthetic/artist perspectives inherent in structural design. Consideration of management, socioeconomic, and ethical issues involved in design and construction of large-scale structures. Introduction to recent developments in sustainable engineering, including green building design and adaptable structural systems.

**CIEN E3010y Introduction to construction: case studies**
3 pts. Lect: 3. Professor Odeh.
Prerequisite(s): Instructor’s permission. Introduces basic principles of how builders construct different types of projects. Shows detailed weekly cases on construction processes for infrastructure as well as building projects. Cases show major differences in constructing different types of projects and highlight challenges/solutions faced by project teams during construction phase. Projects covered include: Tunnels, Bridges, Skyscrapers, Neighborhood Development, Mega Programs, Airports, and Education. Detailed examples of real case studies of iconic national and international projects. Includes site visits to active construction projects.

**CIEN E311fx Uncertainty and risk in civil infrastructure systems**
3.5 pts. Lect: 3. Professor Deodatis.
Prerequisite(s): Working knowledge of calculus. Introduction to basic probability, hazard function, reliability function; stochastic models of natural and technological hazards; extreme value distributions; statistical inference methods; Monte Carlo simulation techniques; fundamentals of integrated risk assessment and risk management; topics in risk-based insurance; case studies involving civil infrastructure systems, environmental systems, mechanical and aerospace systems, construction management.

**CIEN E3121y Structural analysis**
3 pts. Lect: 3. Professor Feng.
Methods of structural analysis. Trusses, arches, cables, frames; influence lines; deflections; force methods; displacement method; computer applications.

**CIEN E3125y Structural design**
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite(s): ENME E3113. Design criteria for varied structural applications, including buildings and bridges; design of elements using steel, concrete, masonry, wood, and other materials.

**CIEN E3126y Computer-aided structural design**
1 pt. Lect: 1. Lab: 1. Instructor to be announced.
Corequisite(s): CIEN E3125. Introduction to software for structural analysis and design with lab. Applications to the design of structural elements and connections. Lab required.

**CIEN E3127x Structural design projects**
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite(s): CIEN E3125 and E3126 or the instructor’s permission. Design of steel members in accordance with AISC 360: moment redistribution in beams; plastic analysis; bearing plates; beam-columns; exact and approximate second-order analysis; design by the Effective Length method and the Direct Analysis method. Design of concrete members in accordance with ACI 318: bar anchorage and development length, bar splices, design for shear, short columns, slender columns. AISC/ASCE NSSBC design project: design of a steel bridge in accordance with National Student Steel Bridge Competition rules; computer simulation and design by using SAP2000.

**CIEN E3128y Design projects**
Prerequisite(s): CIEN E3125 and E3126. Capstone design project in civil engineering. This project integrates structural, geotechnical and environmental/water resources design problems with construction management tasks and sustainability, legal and other social issues. Project is completed in teams, and communication skills are stressed. Outside lecturers will address important current issues in engineering practice. Every student in the course will be exposed with equal emphasis to issues related to geotechnical engineering, water resources/environmental engineering, structural engineering, and construction engineering and management.

**CIEN E3129x Project management for construction**
3 pts. Lect: 3. Professor Chang.
Prerequisite(s): Senior standing in Civil Engineering or instructor’s permission. Introduction to Project Management for design and construction processes. Elements of planning, estimating, scheduling, bidding, and contractual relationships. Computer scheduling and cost control. Critical path method. Design and construction activities. Field supervision.

**CIEN E3141y Soil mechanics**
Prerequisite(s): ENME E3113. Index properties and classification; compaction; permeability and seepage; effective stress and stress distribution; shear strength of soil; consolidation; slope stability.

**CIEE E3250y Hydrosystems engineering**
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): CHEN E3110 or ENME E3161 or equivalent, SIEO W3600 or equivalent, or the instructor’s permission. A quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for nonpoint source pollution. Spatial hydrologic analysis using GIS and watershed models. Note: This course is to be joint listed with CIEN and replaces the previous CIEN 3250.

**CIEE E3255y Environmental control and pollution reduction systems**
3 pts. Lect: 3. Professor Farrarotto.
Prerequisite(s): EEAE E3200 or ENME E3161 or MECE E3100. Review of engineered systems for prevention and control of pollution. Fundamentals of material and energy balances and reaction kinetics. Analysis of engineered systems to address environmental problems, including solid and hazardous waste, and air, water, soil and noise pollution. Life cycle assessments and emerging technologies.

**CIEE E3260y Engineering for community development**
Introduction to the challenges and realities of implementing design solutions with high-risk, low-resource communities in urban and rural settings in both developed and developing countries. History and theory of international development toward preparing globally responsible and informed professionals. Real-world examples of development work across technical sectors including water, sanitation, energy, health, communication technology, shelter, food systems, and environment. Role of engineering in achieving the Sustainable Development Goals. Course projects follow a Design for Impact process resulting in an engineering design, an action plan, and the identification of indicators for impact evaluation.

**CIEN E3303x and y Independent studies in civil engineering for juniors**
1–3 pts. By conference. Members of the faculty. A project on civil engineering subjects approved
by the chair of the department.

CIEN E3304x and y Independent studies in civil engineering for seniors
1–3 pts. By conference. Members of the faculty. A project on civil engineering subjects approved by the chair of the department.

CIEN E3999x, y or s Fieldwork
1–2 pts. Instructor to be announced.
Prerequisite(s): Obtained internship and approval from faculty adviser. CEEM undergraduate students only. Written application must be made prior to registration outlining proposed internship/study program. Final reports required. May not be taken for pass/fail credit or audited. International students must also consult with the International Students and Scholars Office.

CIEN E4010x Transportation engineering
3 pts. Lect: 3. Not offered in 2022–2023. An overview of the planning, design, operation, and construction of urban highways and mass transportation systems. Transportation planning and traffic studies; traffic and highway engineering; rapid transit and railroad engineering.

CEOR E4011x Infrastructure systems optimization
3 pts. Lect: 3. Professor Di.
Prerequisite(s): ENME E3105 or instructor’s permission. Major elements of transportation analyt-ics. Develop basic skills in applying fundamentals of data analytics to transportation data analysis. Apply coding languages (e.g., MATLAB, Python) and visualization tools (e.g., Excel, Carto, R, Processing) to analyze transportation data. Infer policy implications from analytics results.

CIEN E4011y Big data analytics in transportation
3 pts. Lect: 3. Professor Di.
Prerequisite(s): ENME E3105 or instructor’s permission. Major elements of transportation analyt-ics. Develop basic skills in applying fundamentals of data analytics to transportation data analysis. Apply coding languages (e.g., MATLAB, Python) and visualization tools (e.g., Excel, Carto, R, Processing) to analyze transportation data. Infer policy implications from analytics results.

CIEN E4129x and y Managing engineering and construction processes
Prerequisite(s): Graduate standing in Civil Engineering, or instructor’s permission. Introduction to the principles, methods and tools necessary to manage design and construction processes. Elements of planning, estimating, scheduling, bidding and contractual relationships. Valuation of project cash flows. Critical path method. Survey of construction procedures. Cost control and effectiveness. Field supervision.

CIEN E4130x Design of construction systems
3 pts. Lect: 3. Professor Tirolo.
Prerequisite(s): CIEN E3125 or the equivalent, or the instructor’s permission. Introduction to the design of systems that support construction activities and operations. Determination of design loads during construction. Design of excavation support systems, earth retaining systems, temporary supports and underpinning, concrete formwork and shoring systems. Cranes and erection systems. Tunneling systems. Instrumentation and monitoring. Students prepare and present term projects.

CIEN E4131x and y Principles of construction techniques
Prerequisite(s): CIEN E4129 or equivalent. Current methods of construction, cost-effective designs, maintenance, safe work environment. Design functions, constructability, site and environmental issues.

CIEN E4132x Prevention and resolution of construction disputes
Prerequisite(s): CIEN E4129 or equivalent. Contractual relationships in the engineering and construction industry and the actions that result in disputes. Emphasis on procedures required to prevent disputes and resolve them quickly and cost-effectively. Case studies requiring oral and written presentations.

CIEN E4133x Capital facility planning and financing
3 pts. Lect: 3. Professor Chang.
Prerequisite(s): CIEN E4129 or equivalent. Planning and financing of capital facilities with a strong emphasis upon civil infrastructure systems. Project feasibility and evaluation. Design of project delivery systems to encourage best value, innovation and private sector participation. Fundamentals of engineering economy and proj ect finance. Elements of life cycle cost estimation and decision analysis. Environmental, institutional, social and political factors. Case studies from transportation, water supply and wastewater treatment.

CIEN E4134y Construction industry law
Prerequisite(s): Graduate standing or the instruc- tor’s permission. Practical focus upon legal concepts applicable to the construction industry. Provides sufficient understanding to manage legal aspects, instead of being managed by them. Topics include contractual relationships, contract performance, contract flexibility and change orders, liability and negligence, dispute avoid ance/resolution, surety bonds, insurance and site safety.

CIEN E4135y Strategic management in engineering and construction
Core concepts of strategic planning, management and analysis within the construction industry. Industry analysis, strategic planning models and
industry trends. Strategies for information technology, emerging markets and globalization. Case studies to demonstrate key concepts in real-world environments.

CIEN E4136y Entrepreneurship in engineering and construction
Prerequisite(s): Instructor's permission. Capstone practicum where teams develop strategies and business plans for a new enterprise in the engineering and construction industry. Identification of attractive market segments and locations; development of an entry strategy; acquisition of financing, bonding, and insurance; organizational design; plans for recruiting and retaining personnel; personnel compensation/incentives. Invited industry speakers. Priority given to graduate students in Construction Engineering and Management.

CIEN E4137y Managing civil infrastructure systems
3 pts. Lect: 3. Professor Chang.
Prerequisite(s): IEOR E4003, CIEN E4133, or equivalent. Examination of the fundamentals of infrastructure planning and management, with a focus on the application of rational methods that support infrastructure decision-making. Institutional environment and issues. Decision-making under certainty and uncertainty. Capital budgeting and financing. Group decision processes. Elements of decision and finance theory.

CIEN E4138y Real estate finance for construction management
3 pts. Lect: 3. Professor Riordan.
Prerequisite(s): IEOR E2261, CIEN E3129 or permission of instructor. Introduction to financial mechanics of public and private real estate development and management. Working from perspectives of developers, investors and taxpayers, financing of several types of real estate and infrastructure projects are covered. Basics of real estate accounting and finance, followed by in-depth studies of private, public, and public/private-partnership projects and their financial structures. Focused on U.S.-based financing, with some international practices introduced and explored. Financial risks and rewards, and pertinent capital markets and their financing roles. Impacts and incentives of various government programs, such as LEED certification and solar power tax credits. Case studies provide opportunity to compare U.S. practices to several international methods.

CIEN E4139x Theory and practice of virtual design and construction
Prerequisite(s): CIEN E4129 or instructor's permission. History and development of Building Information Modeling (BIM), its uses in design and construction, and introduction to the importance of planning in BIM implementation. Role of visual design and construction concepts and methodologies, including integrated project delivery flow in architecture, engineering, and construction industries from project design, cost estimating, scheduling, coordination, fabrication, installation, and financing.

CIEN E4140x Environmental, health, and safety concepts in construction processes
3 pts. Lect: 3. Professor Haining.
Prerequisite(s): Graduate standing in Civil Engineering and Engineering Mechanics. A definitive review of and comprehensive introduction to construction industry best practices and fundamental concepts of environmental health and safety management systems (EH&S) for the construction management field. How modern EH&S management system techniques and theories not only result in improved safe work environments but ultimately enhance operational processes and performance in construction projects.

CIEN E4141y Public-private partnerships in global infrastructure development
3 pts. Professor Chang.

CIEN E4142x International construction management: theory and practice
3 pts. Lect: 3. Professor Odeh.
Prerequisite(s): CIEN E4129 or instructor’s permission. Complex global construction industry environment. Social, cultural, technological, and political risks; technical, financial, and contractual risk. Understanding of successful global project delivery principals and skills for construction professionals. Industry efforts and trends to support global operational mechanism. Global Case Studies. Engage with industry expert professionals. Student group projects with active ongoing global initiatives.

CIEN E4144x Real estate land development engineering
Comprehensive review of various engineering disciplines in the process of real estate land development. Engineering disciplines covered include civil, infrastructure, transportation planning, environmental planning, permitting, environmental remediation, geotechnical, and waterfront/marine. Overview of land use and environmental law, architecture and urban planning, as related to land development. Discussion of how these subjects affect decisions—cost, schedule, programming—involved in real estate development. Note: Graduate and senior undergraduate students only. Third-year undergraduate students with instructor’s permission.

CIEN E4145x Applied use of AEC data
3 pts. Lect: 2.5. Professors Diaz Gonzalez and Jean.
Digital transformation optimizes day-to-day operations to provide maximum performance in Architecture, Engineering, and Construction (AEC) workflows. Focuses on broadening knowledge of AEC data leading to building data management. Use of open data sets from the design, construction, and operations of buildings to learn and practice data management and its applied use. Major technical topics include Project Management Information System (PMIS) and Facility Management (FM), leading to Digital Twin data management, data processing, and data visualization.

CIEN E4146y Advanced AEC data management
3 pts. Lect: 3. Professors Diaz Gonzalez and Jean.
Prerequisite(s): CIEN E4145. Focused on broadening knowledge of AEC data management. Use of industry data sets from the design, construction, and operations of buildings to learn and practice data management and solve problems by aggregating industry data and creating data-driven reports in a dashboard format. Exploration of industry data through ELT (Extract, Load, Transform) Services. Hands-on learning experiences through a series of workshops and case studies. Course will guide where predictive analysis is performed and how it is used for Project Management Information System (PMIS) and Facility Management (FM), leading to Digital Twin data management, data processing, and data visualization.

CIEE E4163y Sustainable water treatment and reuse
3 pts. Lect: 3. Professor Knowles.
Prerequisite(s): Introductory chemistry (with laboratory) and fluid mechanics. Fundamentals of water pollution and wastewater characteristics. Chemistry, microbiology, and reaction kinetics. Design of primary, secondary, and advanced treatment systems. Small community and residential systems.

CIEN E4212y Structural failures: cases, causes, lessons learned
Prerequisite(s): Working knowledge of structural analysis and design; graduate student standing or instructor’s permission. Review of significant failures, civil/structural engineering design and construction practices, ethical standards and the legal positions as necessary background to forensic engineering. Discussion of standard-of-care. Study of the process of engineering evaluation of structural defects and failures in construction and in service. Examination of the roles, activities, and conduct ethics of the forensic consultant and expert witness. Students are assigned projects of actual cases of nonperformance or failure of steel, concrete, masonry, geotechnical, and temporary structures, in order to perform, discuss, and report their own investigations under the guidance of the instructor.

CIEN E4212y Structural failures: cases, causes, lessons learned
Prerequisite(s): A course each in engineering materials, structural analysis, concrete design, steel design, soil mechanics and foundations, and construction; graduate student standing or instructor’s permission. The nature and causes of structural failures and the lessons learned
from them; insight into failure investigation in the practice of forensic structural engineering. Case histories of actual failures of real-life structures during construction and in service are introduced, examined, analyzed, and discussed. Students are assigned documented cases of failures of structures of various types and materials to review, discuss, and, in some cases, to conduct investigations of the causes and responsibilities. Students are required to prepare written reports and make oral presentations of selected cases.

CIEN E4213x Elastic and inelastic buckling of structures
3 pts. Lect. 3. Professor Valenti.

CIEN E4226y Advanced design of steel structures
3 pts. Lect. 3. Professors Aly and Mosquera.
Prerequisite(s): CIEN E3125 or equivalent. Review of loads and structural design approaches. Material considerations in structural steel design. Behavior and design of rolled steel, welded, cold-formed light-gauge, and composite concrete/steel members. Design of multistory buildings and space structures.

CIEN E4232x Advanced design of concrete structures
3 pts. Lect. 3. Professor Panayiotid. 
Prerequisite(s): CIEN E3125 or equivalent. Design of concrete beams for combined torsion, shear and flexure; moment-curvature relation; bar cut-off locations; design of two-way slabs; strut-and-tie method for the design of deep beams and corbels; gravity and shear wall design; retaining wall design.

CIEN E4233x Design of large-scale bridges
3 pts. Lect. 3. Professor Zoli.
Prerequisite(s): CIEN E3121 or equivalent, and CIEN E3127 or equivalent. Design of large-scale and complex bridges with emphasis on cable-supported structures. Static and dynamic loads, component design of towers, superstructures and cables; conceptual design of major bridge types including arches, cable stayed bridges and suspension bridges.

CIEN E4234y Design of large-scale building structures
3 pts. Lect. 3. Professors Ghasbain, Gottlieb, Molisch, and Tomasetti.
Prerequisite(s): CIEN E3121 and E3127. Modern challenges in the design of large-scale building structures will be studied. Tall buildings, large convention centers, and major sports stadiums present major opportunities for creative solutions and leadership on the part of engineers. This course is designed to expose the students to this environment by having them undertake the complete design of a large structure from initial design concepts on through all the major design decisions. The students work as members of a design team to overcome the challenges inherent in major projects. Topics include overview of major projects, project criteria and interface with architecture, design of foundations and structural systems, design challenges in the post-9/11 environment, and roles, responsibilities, and legal issues.

CIEN E4235x Multihazard design of structures
3 pts. Lect. 3. Professors Daddazio and Mosquera.
Prerequisite(s): CIEN E3125 or E4232 or instructor’s permission. Fundamental considerations of wave mechanics; design philosophies; reliability and risk concepts; basics of fluid mechanics; design of structures subjected to blast; elements of seismic design; elements of fire design; flood considerations; advanced analysis in support of structural design.

CIEN E4236y Design of prestressed concrete structures
3 pts. Lect. 3. Professor Panayiotid. 
Prerequisite(s): CIEN E4232 or instructor’s permission. Properties of materials used in prestressed concrete; pretensioning versus posttensioning; loss of prestress due to elastic shortening, friction, anchorage slip, shrinkage, creep and relaxation; full versus partial prestressing; design of beams for flexure, shear, and torsion; method of load balancing; anchorage zone design; calculation of deflection by the lump-sum and incremental time-step methods; continuous beams; composite construction; prestressed slabs and columns.

CIEN E4237x Architectural design, computation, and method
Prerequisite(s): CIEN E3121 or equivalent. Design of concrete beams for combined torsion, shear and flexure; moment-curvature relation; bar cut-off locations; design of two-way slabs; strut-and-tie method for the design of deep beams and corbels; gravity and shear wall design; retaining wall design.

CIEN E4241x Geotechnical engineering fundamentals
3 pts. Lect. 3. Professor Ling.
Prerequisite(s): CIEN E3141 or instructor’s permission. Bearing capacity and settlement of shallow and deep foundations; earth pressure theories; retaining walls and reinforced soil retaining walls; sheet pile walls; braced excavation; slope stability.

CIEN E4242y Geotechnical earthquake engineering
3 pts. Lect. 3. Professor Ling.
Prerequisite(s): CIEN E3141 or equivalent. Seismicity, earthquake intensity, propagation of seismic waves, design of earthquake motion, seismic site response analysis, in situ and laboratory evaluation of dynamic soil properties, seismic performance of underground structures, seismic performance of port and harbor facilities, evaluation and mitigation of soil liquefaction and its consequences. Seismic earth pressures, slopes stability, safety of dams and embankments, seism
transport and transformation processes in environmental media such as water, air and ecosystems. Engineering applications for addressing environmental problems such as water quality and treatment, air pollutant emissions, and hazardous waste remediation. Presented in the context of current issues facing practicing engineers and government agencies, including legal and regulatory framework, environmental impact assessments, and natural resource management.

**CIEN E4253x** Finite elements and plasticity in geotechnical engineering
Prerequisite(s): CIEN E3141 and ENME E4332.
State-of-the-art computer solutions in geotechnical engineering; 3D consolidation, seepage flows, and soil-structure interaction; element and mesh instabilities.

**CIEE E4257x** Groundwater contaminant transport and remediation

**CIEE E4260x** Urban ecology studio
Prerequisite(s): Senior undergraduate or graduate student standing and instructor's permission. Conjoint studio run with the Graduate School of Architecture, Planning and Preservation (GSAPP) that explores solutions to problems of urban density. Engineering and GSAPP students will engage in a joint project that addresses habitability and sustainability issues in an urban environment, and also provides community service. Emphasis will be on the integration of science, engineering and design within a social context. Interdisciplinary approaches and communication will be stressed.

**CIEN E4300x** Infrastructure materials
Basic concepts of materials science for civil infrastructure materials. Relate composition, structure, processing to engineering properties (e.g., strength, modulus, ductility-malleability, durability). Materials covered include stone, brick, terra cotta, concrete, cast stone, metals, and wood. Overview of sourcing and production, identification, fabrication, chemical, physical and mechanical properties.

**CIEN E4999x and y Fieldwork**
1–2 pts. Instructor to be announced.
Prerequisite(s): Instructor's written approval. May be repeated for credit, but no more than 3 total points may be used for degree credit. Only for Civil Engineering and Engineering Mechanics graduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation required. May not be taken for pass/fail credit or audited.

**COURSES IN ENGINEERING MECHANICS**

See also Courses in Civil Engineering at the beginning of this section.

**ENME E3105x and y Mechanics**
Prerequisite(s): PHYS UN1401, MATH UN1101, MATH UN1102, and MATH UN1201 or APMA E2000. Elements of statics; dynamics of a particle and systems of particles.

**ENME E3106y Dynamics and vibrations**
Prerequisite(s): MATH UN1201 or APMA E2000, and APMA E2101. Corequisite(s): ENME E3105. Kinematics of rigid bodies; momentum and energy methods; vibrations of discrete and continuous systems; eigenvalue problems, natural frequencies and modes. Basics of computer simulation of dynamics problems using MATLAB.

**ENME E3113x Mechanics of solids**
3 pts. Lect: 3. Professor Betti.

**ENME E3114y Experimental mechanics of materials**
Prerequisite(s): ENME E3113. Material behavior and constitutive relations. Mechanical properties of metals and cement composites. Structural materials. Modern construction materials. Experimental investigation of material properties and behavior of structural elements including fracture, fatigue, bending, torsion, buckling.

**ENME E3161x Fluid mechanics**

**ENME E3332x A first course in finite elements**
3 pts. Lect: 3. Professor Fish.
Prerequisite(s): Senior standing or instructor’s permission. Recommended corequisite(s): differential equations. Focus on formulation and application of the finite element to engineering problems such as stress analysis, heat transfer, fluid flow, and electromagnetics. Topics include finite element formulation for one-dimensional problems, such as trusses, electrical and hydraulic systems; scalar field problems in two dimensions, such as heat transfer; and vector field problems, such as elasticity and finally usage of the commercial finite element program. Students taking ENME E3332 cannot take ENME E4332.

**ENME E4111x Advanced mechanics of solids**
3 pts. Lect: 3. Professor Yin.
Stress and deformation formulation in two- and three-dimensional solids; viscoelastic and plastic material in one and two dimension energy methods.

**ENME E4114x Mechanics of fracture and fatigue**
3 pts. Lect: 3. Professor Brügger.
Prerequisite(s): Undergraduate mechanics of solids course. Elastic stresses at a crack; energy and stress intensity criteria for crack growth; effect of plastic zone at the crack; fracture testing applications. Fatigue characterization by stress-life and strain-life; damage index; crack propagation; fail safe and safe life analysis.

**EMME E4115y Micromechanics of composite materials**
3 pts. Lect: 3. Professor Yin.
Prerequisite(s): ENME E4113 or instructor’s approval. An introduction to the constitutive modeling of composite materials: Green’s functions in heterogenous media, Eshelby’s equivalent inclusion methods, eigenstrains, spherical and ellipsoidal inclusions, dislocations, homogenization of elastic fields, elastic, viscoelastic and elastoplastic constitutive modeling, micromechanics-based models.

**ENME E4202y Advanced mechanics**
3 pts. Lect: 3. Professor Smyth.

**ENME E4212x Experimental solid mechanics**
3 pts. Lect: 3. Professor Kidane.
Prerequisite(s): ENME E3113. Experimental techniques, including photoelasticity, strain measurements, digital image correlation, and other optics in stress analysis, emphasizing engineering applications. Fundamental concepts in solid mechanics and measurement science. Performance of high-quality experimental studies.

**ENME E4214y Theory of plates and shells**
3 pts. Lect: 3. Professor Dosgupta.
Prerequisite(s): ENME E3113. Static flexural response of thin, elastic, rectangular, and circular plates. Exact (series) and approximate (Ritz) solutions. Circular cylindrical shells. Axisymmetric and nonaxisymmetric membrane theory. Shells of arbitrary shape.

**ENME E4215x Theory of vibrations**
3 pts. Lect: 3. Professor Betti.

**ENME E4223x Finite element analysis, I**
3 pts. Lect: 3. Professor Waisman.

**ENME E4363y Multiscale computational science and engineering**
3 pts. Lect: 3. Professor Fish.
Prerequisite(s): ENME E4332, elementary computer programming, linear algebra. Introduction to multiscale analysis. Information-passing bridging techniques: among them, generalized mathematical homogenization theory, the heterogeneous multiscale method, variational multiscale method, the discontinuous Galerkin method and the kinetic Monte Carlo–based methods. Concurrent multiscale techniques: domain bridging, local enrichment, and multigrid-based concurrent multiscale methods. Analysis of multiscale systems.

**ENME E6215x Principles and applications of sensors for structural health monitoring**
3 pts. Lect: 2.5. Lab: 0.5. Professor Feng.
Prerequisite(s): ENME E4215. Concepts, principles, and applications of various sensors for sensing structural parameters and nondestructive evaluation techniques for subsurface inspection, data acquisition, and signal processing techniques. Lectures, demonstrations, and hands-on laboratory experiments.

**ENME E6216y Structural health monitoring**
3 pts. Lect: 3. Professor Betti.
Prerequisite(s): ENME E4215 and ENME E4332. Principles of traditional and emerging sensors, data acquisition and signal processing techniques, experimental modal analysis (input-output), operational modal analysis (output-only), model-based diagnostics of structural integrity, long-term monitoring and intelligence maintenance. Lectures and demonstrations, hands-on laboratory experiments.

**ENME E6220y Stochastic engineering mechanics**
3 pts. Lect: 3. Professor Kougioumtzoglou.
Prerequisite(s): CIEN E4111 and ENME E4215 or instructor’s permission. Review of random variables. Random process theory: stationary and ergodic processes, correlation functions and power spectra, non-stationary, non-white and non-Gaussian processes. Uncertainty quantification and simulation of environmental excitations and material/media properties, even when subject to limited/incomplete data: joint time-frequency analysis, sparse representations and compressive sensing concepts and tools. Stochastic dynamics and reliability assessment of diverse engineering systems: complex nonlinear/hysteretic behaviors and/or fractional derivative modeling. Emphasis on solution methodologies based on Monte Carlo simulation, statistical linearization, and Wiener path integral. Examples from civil, marine, mechanical, and aerospace engineering.

**ENME E6315x Theory of elasticity**

**ENME E6320x Computational poromechanics**
Prerequisite(s): ENME E3332 or instructor’s permission. A fluid infiltrating porous solid is a multiphase material whose mechanical behavior is significantly influenced by the pore fluid. Diffusion, advection, capillarity, heating, cooling, and freezing of pore fluid, buildup of pore pressure, and mass exchanges among solid and fluid constituents all influence the stability and integrity of the solid skeleton, causing shrinkage, swelling, fracture, or liquefaction. These coupling phenomena are important for numerous disciplines, including geophysics, biomechanics, and material sciences. Fundamental principles of poromechanics essential for engineering practice and advanced study on porous media. Topics include balance principles, Biot’s poroelasticity, mixture theory, constitutive modeling of path independent and dependent multiphase materials, numerical methods for parabolic and hyperbolic systems, inf-sup conditions, and common stabilization procedures for mixed finite element models, explicit and implicit time integrators, and operator splitting techniques for poromechanics problems.

**ENME E6333y Finite element analysis, II**
3 pts. Lect: 3. Professor Waisman.

**ENME E6364x Nonlinear computational mechanics**
3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): ENME E4332 or equivalent, elementary computer programming, linear algebra. The formulations and solution strategies for finite element analysis of nonlinear problems are developed. Topics include the sources of nonlinear behavior (geometric, constitutive, boundary condition), derivation of the governing discrete equations for nonlinear systems such as large displacement, nonlinear elasticity, rate independent and dependent plasticity and other nonlinear constitutive laws, solution strategies for nonlinear problems (e.g., incrementation, iteration), and computational procedures for large systems of nonlinear algebraic equations.

**ENME E6370y Turbulence theory and modeling**
3 pts. Lect: 3. Professor Giotetto.
Prerequisite(s): ENME E3161 or equivalent, Ordinary and partial differential equations. Turbulence phenomenology, spatial and temporal scales in turbulent flows, statistical description, filtering and Reynolds decomposition, equations governing the resolved flow, fluctuations and their energetics, turbulence closure problem for RANS and LES, two-equation turbulence models, and second-moment closures.
ENME E8310x Advanced continuum mechanics
3 pts. Lect: 3. Professor Dasgupta.
Prerequisite(s): MECE E6422 and E6423. Open to Ph.D. students and to M.S. students with instructor’s permission. Review of continuum mechanics in Cartesian coordinates; tensor calculus and the calculus of variation; large deformations in curvilinear coordinates; electricity problems and applications.

ENME E8320x Viscoelasticity and plasticity
4 pts. Lect: 3. Professor Dasgupta.
Prerequisite(s): ENME E6315 or equivalent, or instructor’s permission. Constitutive equations of viscoelastic and plastic bodies. Formulation and methods of solution of the boundary value, problems of viscoelasticity and plasticity.

ENME E8323y Nonlinear vibrations

COURSES IN GRAPHICS
GRAP E4005y Computer graphics in engineering
3 pts. Lect: 3. Professor Dasgupta.
Prerequisite(s): Any programming language and linear algebra. Numerical and symbolic (algebraic) problem solving with Mathematica. Formulation for graphics application in civil, mechanical, and bioengineering. Example of two-and three-dimensional curve and surface objects in C++ and Mathematica; special projects of interest to electrical and computer science.
COMPUTER ENGINEERING PROGRAM

Administered by both the Electrical Engineering and Computer Science Departments through a joint Computer Engineering Committee. Student records are kept in the Electrical Engineering Department.

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compeng.columbia.edu

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469 CSB

COMPUTER ENGINEERING COMMITTEE
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Xiaofang Fred Jiang, 
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Associate Professor of Computer Science
Vishal Misra, 
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Mingoo Seok, 
Associate Professor of Electrical Engineering
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Professor of Computer Science
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Professor of Electrical Engineering and Biomedical Engineering
Charles A. Zukowski, 
Professor of Electrical Engineering
Gil Zussman, 
Professor of Electrical Engineering

The computer engineering program is run jointly by the Computer Science and Electrical Engineering departments. It offers both B.S. and M.S. degrees.

The program covers some of engineering’s most active, exciting, and critical areas, which lie at the interface between CS and EE. The focus of the major is on computer systems involving both digital hardware and software.

Some of the key topics covered are computer design (i.e., computer architecture); embedded systems (i.e., the design of dedicated hardware/software for cell phones, automobiles, robots, games, and aerospace); digital and VLSI circuit design; computer networks; design automation (i.e., CAD); and parallel and distributed systems (including architectures, programming, and compilers).

Students in the programs have two “home” departments. The Electrical Engineering Department maintains student records and coordinates advising appointments.

UNDERGRADUATE PROGRAM

This undergraduate program incorporates most of the core curricula in both electrical engineering and computer science so that students will be well prepared to work in the area of computer engineering, which substantially overlaps both fields. Both hardware and software aspects of computer science are included, and, in electrical engineering, students receive a solid grounding in circuit theory and in electronic circuits. The program includes several electrical engineering laboratory courses as well as the Computer Science Department’s advanced programming course. Detailed lists of requirements can be found at compeng.columbia.edu.

Students will be prepared to work on all aspects of the design of digital hardware, as well as on the associated software that is now often an integral part of computer architecture. They will also be well equipped to work in the growing field of telecommunications. Students will have the prerequisites to delve more deeply into either hardware or software areas, and enter graduate programs in computer science, electrical engineering, or computer engineering. For example, they could take more advanced courses in VLSI, communications theory, computer architecture, electronic circuit theory, software engineering, or digital design.

Minors in electrical engineering and computer science are not open to computer engineering majors, due to excessive overlap.

Technical Electives

The Computer Engineering Program includes 15 points of technical electives. All must be 3000-level or above, technical, and must not have significant overlap with other courses taken for the major. Adviser approval of technical electives is required.

Most courses at the 3000-level or above offered by the Computer Science and Electrical Engineering departments are eligible, and up to two from outside those departments can be considered for approval as well. If a department advertises that one of its courses can be used as a technical elective that does not necessarily mean it will be approved as a technical elective in the computer engineering program. There must be sufficient technical content and computer engineering connection within the entire 15 points, so approval of some courses may depend on the other electives chosen. Economics courses cannot be used as technical electives. COMS
## COMPUTER ENGINEERING PROGRAM: FIRST AND SECOND YEARS
### EARLY-STARTING STUDENTS

<table>
<thead>
<tr>
<th></th>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATHEMATICS</strong></td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0) either semester</td>
<td>APMA E2101 (3)†</td>
</tr>
<tr>
<td><strong>PHYSICS</strong> (three tracks, choose one)</td>
<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>Lab UN1494 (3) or chem. lab UN1500 (3)</td>
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<tr>
<td></td>
<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td>Lab UN1494 (3) or chem. lab UN1500 (3)</td>
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<tr>
<td></td>
<td>UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
<td>Lab UN3081 (2) or chem. lab UN1500 (3)</td>
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<tr>
<td><strong>CHEMISTRY</strong></td>
<td>one-semester lecture (3–4)</td>
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<td></td>
<td>UN1403 or UN1404 or UN2045 or UN1604</td>
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</tr>
<tr>
<td></td>
<td>Lab UN1500 (3) either semester or physics lab UN1494 (3)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>CORE REQUIRED COURSES</strong></td>
<td>ELEN E1201 (3.5)</td>
<td></td>
<td>ELEN E3801 (3.5) Signals and systems</td>
<td>COMS W3134 (3) or W3137 (4) Data structures CSEE W3827 (3) Fund. of computer sys.</td>
</tr>
<tr>
<td><strong>REQUIRED LABS</strong></td>
<td>ELEN E3084 (1)  Signals and systems lab</td>
<td>ELEN E3082 (1) Digital systems lab</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
<td>CC1010 (3) either semester</td>
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<tr>
<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
<td></td>
<td></td>
<td>HUMA CC1001, COCI CC1101, or Global Core (3–4)</td>
<td>HUMA CC1002, COCI CC1102, or Global Core (3–4) ECON UN1105 (4) and UN1155 recitation (0)</td>
</tr>
<tr>
<td><strong>COMPUTER SCIENCE</strong></td>
<td>ENGI E1006 (3)</td>
<td>COMS W1004 (3) or W1007 (3)</td>
<td>COMS W3203 (3) Discrete math.</td>
<td></td>
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<tr>
<td><strong>PHYSICAL EDUCATION</strong></td>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
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<tr>
<td><strong>THE ART OF ENGINEERING</strong></td>
<td>ENGI E1102 (4) either semester</td>
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</tbody>
</table>

1. APMA E2101 may be replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101, or MATH UN2010, or COMS W3251.
2. Some of these courses can be postponed to the junior or senior year to make room for taking the required core computer engineering courses.
## COMPUTER ENGINEERING: THIRD AND FOURTH YEARS
### EARLY-STARTING STUDENTS

<table>
<thead>
<tr>
<th>CORE REQUIRED COURSES</th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEOR E3658 (3)&lt;sup&gt;1&lt;/sup&gt; Probability</td>
<td>ELEN E3331 (3) Electronic circuits</td>
<td>COMS W4118 (3) Operating systems or COMS W4115 (3) Programming lang.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMS W3157 (4) Advanced programming</td>
<td>COMS W3261 (3) Computer sci. theory</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3201 (3.5) Circuit analysis</td>
<td>(Choose 3 of 6) CSEE W4119 (3) Computer networks, EECS E4321 (3) Digital VLSI circuits, CSEE W4823 (3) Advanced logic design, CSEE W4824 (3) Computer architecture, CSEE W4840 (3) Embedded systems, CSEE W4868 (3) System-on-chip platforms</td>
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</table>

<table>
<thead>
<tr>
<th>REQUIRED LABS</th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELEN E3081 (1) Circuit analysis lab</td>
<td>ELEN E3083 (1) Electronic circuits lab</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TECH&lt;sup&gt;2&lt;/sup&gt; Electives</th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 points required; see details within the text</td>
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</table>

<table>
<thead>
<tr>
<th>NONTECH Electives</th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement) or seas.columbia.edu for details (administered by the advising dean)</td>
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<thead>
<tr>
<th>TOTAL POINTS&lt;sup&gt;3&lt;/sup&gt;</th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
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<tbody>
<tr>
<td>17.5</td>
<td>17</td>
<td>15</td>
<td>15</td>
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</tbody>
</table>

For a discussion about programming languages used in the program, please see compeng.columbia.edu.

<sup>1</sup> SIEO W3600, STAT GU4203, and STAT GU4001 can be used instead of IEOR E3658, but W3600 and GU4001 may not provide enough probability background for elective courses such as ELEN E3701. Students completing an economics minor who want such a background can take IEOR E3658 and augment it with SIEO E4307.

<sup>2</sup> The total points of technical electives is reduced to 12 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010, or COMS W3251. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can apply for this waiver, but the courses must have been at an advanced level for this to be considered.

<sup>3</sup> “Total points” assumes that 20 points of nontechnical electives and other courses are included.

W3101/W3102 courses, and not-very-technical courses within the school of engineering, cannot be used as technical electives either.

**Starting Early**

Students are strongly encouraged to begin taking core computer engineering courses as sophomores. They start with ELEN E1201: Introduction to electrical engineering in the second semester of their first year and may continue with other core courses one semester after that. For sample “early-starting” and “late-starting” programs, see the degree track charts. It must be emphasized that these charts present examples only; actual schedules may be customized in consultation with academic advisers.

**GRADUATE PROGRAM**

The Computer Engineering Program offers a course of study leading to the degree of Master of Science (M.S.). The basic courses in the M.S. program come from the Electrical Engineering and Computer Science Departments. Students completing the program are prepared to work (or study further) in such fields as digital computer design, digital communications, and the design of embedded computer systems.

Applicants are generally expected to have a bachelor’s degree in computer engineering, computer science, or electrical engineering with at least a 3.2 GPA in technical courses. The Graduate Record Examination (GRE), General Test only, is required of all applicants.

Students must take at least 30 points of courses at Columbia University at or above the 4000 level. These must include at least 15 points from the courses listed below that are deemed core to computer engineering. Other courses may be chosen with the prior approval of a faculty adviser in the Computer Engineering Program.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.
## COMPUTER ENGINEERING PROGRAM: FIRST AND SECOND YEARS
### LATE-STARTING STUDENTS

<table>
<thead>
<tr>
<th></th>
<th>SEMESTER I</th>
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<th>SEMESTER IV</th>
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<tbody>
<tr>
<td><strong>MATHEMATICS</strong></td>
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<td></td>
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<tr>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td></td>
<td></td>
<td>APMA E2000 (4) and E2001 (0) either semester</td>
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<td></td>
<td>APMA E2101 (3)(1)</td>
</tr>
<tr>
<td><strong>PHYSICS</strong> (three tracks, choose one)</td>
<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>Lab UN1494 (3) or chem. lab UN1500 (3)</td>
<td></td>
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<tr>
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<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td>Lab UN1494 (3) or chem. lab UN1500 (3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
<td>Lab UN3081 (2) or chem. lab UN1500 (3)</td>
<td></td>
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<tr>
<td><strong>CHEMISTRY</strong></td>
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<tr>
<td>one-semester lecture (3–4)</td>
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<tr>
<td>UN1403 or UN1404 or</td>
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<tr>
<td>UN2045 or UN1604</td>
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<tr>
<td>Lab UN1500 (3) either semester or physics lab UN1494 (3)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>CORE REQUIRED COURSES</strong></td>
<td>ELEN E1201 (3.5)(2)</td>
<td>Intro. to elec. eng. (either semester)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
<td></td>
<td>CC1010 (3) each semester</td>
<td></td>
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</tr>
<tr>
<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
<td></td>
<td>HUMA CC1001, COCI CC1101, or Global Core (3–4)</td>
<td>HUMA CC1002, COCI CC1102, or Global Core (3–4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HUMA UN1121 or UN1123 (3)</td>
<td>ECON UN1105 (4) and UN1155 recitation (0)</td>
<td></td>
</tr>
<tr>
<td><strong>COMPUTER SCIENCE</strong></td>
<td>ENGI E1006 (3)</td>
<td>COMS W1004 (3) or W1007 (3)</td>
<td>W3203 (3) Discrete math.</td>
<td></td>
</tr>
<tr>
<td><strong>PHYSICAL EDUCATION</strong></td>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>THE ART OF ENGINEERING</strong></td>
<td>ENGI E1102 (4) each semester</td>
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</tbody>
</table>

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1 APMA E2101 may be replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101, or MATH UN2010, or COMS W3251.

2 Transfer and combined-plan students are expected to have completed the equivalent of the first- and second-year program listed above before starting their junior year. Note that this includes some background in discrete math (see COMS W3203) and electronics circuits (see ELEN E1201). Transfer and combined-plan students are also expected to be familiar with Java before they start their junior year. If students must take the one-point Java course (COMS W3101-03) junior year, prerequisite constraints make it difficult to complete the remaining computer engineering program by the end of the senior year.
<table>
<thead>
<tr>
<th></th>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CORE REQUIRED COURSES</strong></td>
<td>IEOR E3658 (3)† Probability</td>
<td>COMS W3157 (4)</td>
<td>CWS W4118 (3) Operating systems</td>
<td>or</td>
</tr>
<tr>
<td></td>
<td>COMS W3134 (3) or W3137 (4) Data structures</td>
<td>ELEN E3331 (3)</td>
<td>CWS W4115 (3) Programming lang.</td>
<td>(Choose 3 of 6)</td>
</tr>
<tr>
<td></td>
<td>ELEN E3201 (3.5) Circuit analysis</td>
<td>ELEN E3261 (3)²</td>
<td>CWS W4823 (3) Advanced logic</td>
<td>CSEE W4119 (3) Computer networks, EECS E4321 (3)</td>
</tr>
<tr>
<td></td>
<td>ELEN E3801 (3.5) Signals and</td>
<td>Models of comp.</td>
<td>CSEE W4824 (3) Computer architecture, CSEE W4840 (3) Embedded systems, CSEE W4868 (3) System-on-chip platforms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>systems</td>
<td>CSEE W3827 (3) Fund. of computer systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>REQUIRED LABS</strong></td>
<td>ELEN E3081 (1)³ Circuit analysis</td>
<td>ELEN E3083 (1)³</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>lab</td>
<td>Electronic circuits</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>ELEN E3084 (1)³ Signals and</td>
<td>ELEN E3082 (1)³</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>systems lab</td>
<td>Digital systems lab</td>
<td></td>
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<tr>
<td><strong>ELECTIVES</strong></td>
<td>15 points required; see details within the text</td>
<td></td>
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<tr>
<td><strong>NONTECH</strong></td>
<td>Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement)</td>
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<tr>
<td></td>
<td>or seas.columbia.edu for details (administered by the advising dean)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL POINTS</strong></td>
<td>15</td>
<td>18</td>
<td>15</td>
<td>18</td>
</tr>
</tbody>
</table>

For a discussion about programming languages used in the program, please see compeng.columbia.edu.

1 SIEO W3600, STAT GU4203, and STAT GU4001 can be used instead of IEOR E3658, but W3600 and GU4001 may not provide enough probability background for elective courses such as ELEN E3701. Students completing an economics minor who want such a background can take IEOR E3658 and augment it with IEOR E4307.

2 COMS W3261 can be taken one semester later than pictured.

3 If possible, ELEN E3081 and ELEN E3084 should be taken along with ELEN E3201 and ELEN 3801, respectively, and ELEN E3083 and ELEN E3082 taken with ELEN E3331 and CSEE W3827 respectively.

4 The total points of technical electives is reduced to 12 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010, or COMS W3251. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can apply for this waiver, but the courses must have been at an advanced level for this to be considered.

5 Assuming technical electives taken Semesters VII and VIII, and 9 points of nontechnical electives taken Semesters VI, VII, and VIII.

**Core Computer Engineering Courses**
- CSEE W4119: Computer networks
- CSEE W4140: Networking laboratory
- EECS E4321: Digital VLSI circuits
- EECS E4750: Hybrid comp. for sig. & data proc.
- EECS E4764: IoT-intelligent & connected sys.
- EECS W4823: Advanced logic design
- EECS W4824: Computer architecture
- EECS W4840: Embedded systems
- EECS W4868: Systems-on-chip platforms
- EECS E4951: Wireless networks & systems
- EECS E6180: Modeling & performance eval
- EECS E6321: Adv. digital electronic circuits
- EECS E6322: VLSI hard. arch. for sig. proc. & m1
- COMS E6424: Hardware security
- COMS E6765: Internet of things—sys. & physical data analytics

**CSEE E6624**: Parallel computer architecture
**CSEE E6681**: CAD of digital systems
**CSEE E6863**: Formal verification of hardware/software systems
**CSEE E6868**: Embedded scalable platforms
**EECS E6890**: Advanced computer networks
**EECS E6897**: Distributed storage systems
**COMS W6998**: Topics in computer science: Data networks

The overall program must include at least 12 points of 6000-level ELEN, EECS, CSEE, or COMS courses (exclusive of seminars). No more than 9 points of research project may be taken for credit. No more than 3 points of a nontechnical elective (at or above the 4000 level and with adviser approval) may be included. A minimum GPA of at least 2.7 must be maintained, and all degree requirements must be completed within five years of the beginning of the first course credited toward the degree.
The function and influence of the computer is pervasive in contemporary society. Today’s computers process the daily transactions of international banks, the data from communications satellites, the images in video games, and even the fuel and ignition systems of automobiles.

Computer software is as commonplace in education and recreation as it is in science and business. There is virtually no field or profession that does not rely upon computer science for the problem-solving skills and the production expertise required in the efficient processing of information. Computer scientists, therefore, function in a wide variety of roles, ranging from pure theory and design to programming and marketing.

The computer science curriculum at Columbia places strong emphasis both on theoretical computer science and mathematics and on applied aspects of computer technology. A broad range of upper-level courses is available in such areas as artificial intelligence, machine learning, computer graphics, computer vision, robotics, computational complexity and the analysis of algorithms, combinatorial methods, computer architecture, computer-aided digital design, computer communications, databases, mathematical models for computation, optimization, and software systems.

Laboratory Facilities
The department has a dedicated computing work space for students with dedicated workstations as well as audiovisual equipment for group meetings, specialized office hours, and small seminars. The department also has its own 120-seat lecture hall featuring flexible seating, a dedicated podium computer, and presentation equipment, as well as video conferencing capabilities.

The department maintains its own dedicated Data Center for computational research, storage, and administrative systems. It houses several computer clusters for research and student use and several hundred research systems, all supported by more than a petabyte of storage. Services offered to the department utilize virtual machines (VMWare supporting more than 500 instances) and containerization (100 Docker containers).

In addition, the department has numerous individual laboratories with specialized hardware dedicated to particular research areas, including, but not limited to, robotics, computer vision, computer networks, computer security, computer architecture, speech processing, machine learning, and natural language processing.

UNDERGRADUATE PROGRAM
Computer science majors at Columbia study an integrated curriculum, partially in areas with an immediate relationship to the computer, such as programming languages, operating
systems, and computer architecture, partially in artificial intelligence and associated application areas such as computational biology, machine learning, and robotics, and partially in theoretical computer science and mathematics. Thus, students obtain the background to pursue their interests both in applications and in theoretical developments.

Practical experience is an essential component of the computer science program. Undergraduate students are often involved in advanced faculty research projects using state-of-the-art computing facilities. Qualified majors sometimes serve as consultants at Columbia University Information Technology (CUIT), which operates several computer labs at convenient locations on the campus.

Upper-level students in computer science may assist faculty members with research projects, particularly in the development of software. Ongoing faculty projects span a wide range of research areas including computer science theory, graphics and user interfaces, natural language processing and speech, security and privacy, computational biology, software systems, computer engineering, networking, vision and robotics, machine learning, and artificial intelligence. Students are strongly encouraged to arrange for participation by consulting individual faculty members and by attending the Computer Science Research Fair held at the beginning of each semester.

Most graduates of the computer science program at Columbia step directly into career positions in
computer science with industry or government, or continue their education in graduate degree programs. Many choose to combine computer science with a second career interest by taking additional programs in business administration, medicine, or other professional studies.

For further information on the undergraduate computer science program, please see the home page and the Quick Guide (cs.columbia.edu/education/undergraduate/).

The CS Major Requirements

The Undergraduate program consists of a minimum of 63 or 64 points and includes the following: ENGI E1006 which is a prerequisite to the CS major, the CS Core consisting of 7-8 classes (24-25 points), 7 Track courses (21 points), and 15 points of general technical electives.

Note: All courses toward the CS major must be taken for a letter grade. A maximum of one course worth no more than 4 points passed with a grade of D may be counted towards the major.

Any course exceptions to the noted requirements toward the CS major, all thesis, projects, special topics, and general technical electives must be approved by the faculty adviser in writing.

Prerequisite to the CS Major

ENGI E1006 Introduction to computing for engineers and applied scientists. All CS majors are required to take this course and it is recommended that they do so in their first or second semester.

The Computer Science Core

The core of the major consists of 7 or 8 courses plus one prerequisite course for a total of 8 or 9 courses. These courses provide the foundation for the tracks and advanced courses. Beginning with the class of 2023 the CS Core requirements will change as noted below.

The following are required courses toward the CS Core for the class of 2023 and beyond:

1. COMS W1004 or W1007 (3)
2. COMS W3134 (3) or W3137 (4)
3. COMS W3157 (4)
4. COMS W3203 (4)
5. COMS W3251 (4) (recommended) or MATH UN2010 or APMA E2101 or E3101 (3)
6. COMS W3261 (3)
7. CSEE W3827 (3)

The following are required courses toward the CS Core for the class of 2022 and earlier:

1. COMS W1004 or W1007 (3)
2. COMS W3134 (3) or W3137 (4)
3. COMS W3157 (4)
4. COMS W3203 (4)
5. COMS W3251 (4) or MATH UN2010 or APMA E2101 or E3101 (3)
6. COMS W3261 (3)
7. CSEE W3827 (3)
8. STAT GU4001 or IEOR E4150 (3)

Tracks

In addition, an advanced track is available by invitation for qualified students who desire an extra opportunity for advanced learning. Any course exceptions to the track requirements must be approved by the faculty adviser. All thesis, projects, special topics, and general technical electives must also be approved by the faculty adviser. The 6 predefined tracks are as follows:

- Foundations of Computer Science
- Software Systems
- Digital Systems
- Intelligent Systems
- Applications
- Vision, Graphics, Interactions, and Robotics

Undergraduate Thesis

A student may, with adviser approval, choose to complete a thesis in place of up to 6 points of track elective or general technical elective points. A thesis consists of an independent theoretical or experimental investigation of an appropriate problem in computer science carried out under the supervision of a Computer Science Department faculty member. A formal written report is mandatory and an oral presentation may also be required.

General Technical Electives

An additional 15 points of adviser approved general technical electives at the 3000 level or above are also required. These general technical electives should be in mathematics, science, engineering, or closely related disciplines and should be approved by your faculty adviser.
Advanced Placement
Students who pass the Computer Science Advanced Placement (AP) Exam with a 4 or 5 will receive 3 points of credit and an exemption from COMS W1004.

Track 1: Foundations of CS Track
The foundations track is suitable for students who are interested in algorithms, computational complexity, and other areas of theoretical Computer Science.

REQUIRED: 6 points
CSOR W4231: Analysis of algorithms
COMS W4236: Introduction to computational complexity

ELECTIVES: 15 points from the following list:
Any COMS BC3xxx course (with adviser approval)
MATH UN3020: Number theory and cryptography
MATH UN3025: Making, breaking codes
COMS W3998: Projects in Computer Science*
COMS W4203: Graph theory
MATH GU4032: Fourier analysis
MATH GU4041: Introduction to modern algebra I
MATH GU4042: Introduction to modern algebra II
MATH GU4061: Introduction to modern analysis I
MATH GU4155: Probability theory
COMS W4252: Computational learning theory
COMS W4261: Introduction to cryptography
APMA E4300: Numerical methods
IEOR E4407: Game theoretic models of operation
PHIL GU4431: Set theory
CSPH GU4801: Mathematical logic I
CSPH GU4802: Mathematical logic II: incompleteness
COMS W4901: Projects in computer science*
COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)
COMS E6232: Analysis of algorithms, II
MATH GR6238: Enumerative combinatorics
COMS E6253: Advanced topics in computational learning theory
COMS E6261: Advanced cryptography
IEOR E6400: Scheduling: deterministic models
IEOR E6603: Combinatorial optimization
IEOR E6606: Advanced topics in network flows
IEOR E6608: Integer programming
IEOR E6610: Approximation algorithms
EECS E6616: Convex optimization
IEOR E6613: Optimization I (4.5)
IEOR E6614: Optimization II (4.5)
IEOR E6711: Stochastic models I
IEOR E6712: Stochastic models II
ELEN E6717: Information theory
ELEN E6718: Algebraic coding theory
ELEN E6970: Resource allocation and networking games
COMS E6998-E6999: Topics in computer science, I and II (with adviser approval)*

* With adviser approval, may be repeated for credit

Note: No more than 6 points of project/thesis courses (COMS W3902, W3998, W4901) can count toward the major.

Students who declared their Computer Science major prior to Fall 2016 may also count COMS W4241, W4205, W4281, W4444, W4771, and W4772 as elective courses.

Track 2: Software Systems Track
The software systems track is for students interested in networks, programming languages, operating systems, software engineering, databases, security, and distributed systems.

REQUIRED: 9 points
COMS W4115: Programming languages and translators
COMS W4118: Operating systems
CSE W4119: Computer networks

ELECTIVES: 12 points from the following list:
COM S W3107: Clean object-oriented design
Any COMS BC3xxx course (with adviser approval)
COMS W3902: Undergraduate thesis*
COMS BC3930: Creative embedded systems
COMS W3998: Undergraduate projects in computer science*
COMS W41xx course
COM S W4444: Programming and problem solving
Any COMS W48xx course
COMS W4901: Projects in computer science*
COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)

Any COMS E61xx course (with adviser approval)
Any COMS E68xx course (with adviser approval)
COMS E6998-E6999: Topics in computer science, I and II (with adviser approval)*

* With adviser approval, may be repeated for credit

Note: No more than 6 points of project/thesis courses (COMS W3902, W3998, W4901) can count toward the major.

Track 3: Intelligent Systems Track
The intelligent systems track is for students interested in machine learning, robots, and systems capable of exhibiting “human-like” intelligence. A total of seven required breadth and elective courses are to be chosen from the following schedule.

REQUIRED: 9 Points from:
COMS W4701: Artificial intelligence
COMS W4705: Natural language processing
COMS W4706: Spoken language processing
COMS W4731: Computer vision I: first principles
COMS W4733: Computational aspects of robotics
COMS W4771: Machine learning

ELECTIVES: 12 points required
Up to 12 points from the following list:
Any COMS BC3xxx course (with adviser approval)
COMS W4165: Pixel processing
COMS W4252: Computational learning theory
COMS W47xx course if not used as a required course
COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)
Any COMS W67xx course
COMS E6998-E6999: Topics in computer science, I and II (with adviser approval)*

Up to 6 points from the following list:
COMS W3902: Undergraduate thesis*
COMS W3998: Undergraduate projects in computer science*
COMS W4901: Projects in computer science*

Up to 3 points from the following list:
COMS W4111: Database systems
COMS W4160: Computer graphics
COMS W4170: User interface design
COMS W4999: Computing and the humanities

* With adviser approval, may be repeated for credit

Note: No more than 6 points of project/thesis courses (COMS W3902, W3998, W4901) can count toward the major.

Track 4: Applications Track
The applications track is for students interested in the implementation of interactive multimedia applications for the internet and wireless networks.

REQUIRED: 6 points
COMS W4111: Introduction to databases
COMS W4170: User interface design

ELECTIVES: 15 points from the following list:
COMS W3107: Clean object-oriented design
Any COMS BC3xxx course (with adviser approval)
COMS BC3420: Privacy in a networked world
COMS BC3430: Computational sound
COMS BC3930: Creative embedded systems
COMS W3902: Undergraduate thesis*
COMS W3998: Undergraduate projects in computer science*
COMS W41xx course
COMS W4901: Projects in computer science*
COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)

Any COMS E61xx course (with adviser approval)
Any COMS E68xx course (with adviser approval)
COMS E6998-E6999: Topics in computer science, I and II (with adviser approval)*

* With adviser approval, may be repeated for credit
Note: No more than 6 points of project/thesis courses (COMS W3902, W3998, W4901) can count toward the major.

**Track 5: Vision, Interaction, Graphics, and Robotics Track**

The vision, interaction, graphics, and robotics track focus on visual information with topics in vision, graphics, human-computer interaction, robotics, modeling, and learning. Students learn about fundamental ways in which visual information is captured, manipulated, and experienced.

REQUIRED: 6 points from:
- COMS W4160: Computer graphics
- COMS W4731: Computer vision I: first principles
- COMS W4167: Computer animation

ELECTIVES: 15 points from the following list:
- Any COMS BC3xxx course (with adviser approval)
- COMS W4160, W4731, or W4167 (whichever is not taken as two courses above)
- COMS W3902: Undergraduate thesis*
- COMS W3998: Undergraduate projects in computer science*
- COMS W4162: Advanced computer graphics
- COMS W4165: Pixel processing
- COMS W4170: User interface design
- COMS W4172: 3D user interface design
- COMS W4701: Artificial intelligence
- COMS W4732: Computer Vision II
- COMS W4733: Computational aspects of robotics
- COMS W4735: Visual interfaces to computers
- COMS W4771: Machine learning
- COMS W4901: Projects in computer science*
- COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)
- COMS W4995: Special topics in CS (video game technology)
- Any COMS E691x course (with adviser approval)
- COMS E6998-E6999: Topics in computer science, I and II (with adviser approval)*

* With adviser approval, may be repeated for credit

Note: No more than 6 points of project/thesis courses (COMS W3902, W3998, W4901) can count toward the major.

**Track 6: Digital Systems Track**

The digital systems track is for students interested in working at the interface of hardware and software. Subjects include digital design, computer architecture (both sequential and parallel) and embedded systems.

REQUIRED: 3 points
- CSEE W4824: Computer architecture

Plus 3 points from:
- CSEE W4823: Advanced logic design
- CSEE W4840: Embedded systems

EECS E4340: Computer hardware design

Plus 3 points from:
- COMS W4115: Programming languages and translators
- COMS W4118: Operating systems
- COMS W4130: Parallel programming

ELECTIVES: 12 points from the following list:
- Any COMS BC3xxx course (with adviser approval)
- COMS BC3930: Creative embedded systems
- COMS W3902: Undergraduate thesis*
- COMS E3998: Undergraduate projects in computer science*
- Any COMS/CSEE W41xx course
- Any COMS/CSEE W48xx course
- COMS W4995-W4996: Special topics in computer science, I and II (with adviser approval)
- CSEE E4901: Projects in computer science
- COMS E6998-E6999: Topics in computer science, I and II (with adviser approval)*
- CSEE E6824: Parallel computer architecture*
- CSEE E6847: Distributed embedded systems*
- CSEE E6861: CAD of digital systems**
- CSEE E6868: Embedded scalable platforms**
- COMS E6998-E6999: Topics in computer science, I and II (with adviser approval)*

* With adviser approval, may be repeated for credit
**With adviser approval.

Note: No more than 6 points of project/thesis courses (COMS W3902, W3998, W4901) can count toward the major.
Track 7: Advanced

The advanced track of the B.S. in Computer Science provides extra opportunity for advanced learning. It comprises accelerated versions of the other six tracks. Entry is only by collective faculty invitation, extended to students who have already completed the core courses and the required courses for one of those tracks.

REQUIRED TRACK COURSES

A student designates one of the six other track areas and completes the set of required track courses for that track, prior to entry into the Advanced Track. There are two or three courses, depending on the designated area.

ELECTIVES

At least 6 points of 4000-level lecture courses from the menu for the designated track, plus 6 points of 6000-level courses in the designated track area.

THESIS

There is a required 6-point senior thesis.

INVITATION

Only the top 20 percent of computer science majors in course performance in computer science courses will be considered for invitation during the junior year. (A student in the advanced track who does not maintain this status may be required to return to their previously selected track area.)

GRADUATE PROGRAMS

The Department of Computer Science offers graduate programs leading to the degree of Master of Science and the degree of Doctor of Philosophy. The Graduate Record Examination (GRE) is required for admission to the department's graduate programs. Applicants for September admission should take the GREs by October of the preceding year. Applicants for January admission should take these exams by April of the preceding year.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

M.S. in Computer Science Program

The Master of Science (M.S.) program is intended for students with a bachelor's degree in Computer Science or a strongly related field who wish to broaden and deepen their understanding of computer science. Columbia University and the New York City environment provide excellent career opportunities with multiple industries. The program provides a unique opportunity to develop leading-edge in-depth knowledge of specific computer science disciplines.

Students in the M.S. program must complete a total of 30 points with a GPA of at least 2.7. Every student selects a track that focuses on a particular field of computer science. There are currently eight predefined M.S. tracks: Computational Biology; Computer Security; Foundations of Computer Science; Machine Learning; Natural Language Processing; Network Systems; Software Systems; Vision, Graphics, Interaction, and Robotics. Every track has a set of required courses and a wide range of elective courses that allow the students flexibility in designing their program according to their interests, under the guidance of a faculty adviser. Besides the eight predefined tracks, there is also the option of a M.S. Personalized track for students who want to study an area of computer science that is not covered by one of the eight tracks, and the option of the M.S. Thesis track for students who want to do extensive research in a subfield and write an M.S. thesis, under the supervision of a faculty member. Students in all the tracks are encouraged to pursue research if they wish, and may participate in research projects with the faculty. The faculty in the department conduct research in all areas of computer science. For detailed information on the M.S. program, please see cs.columbia.edu/education/ms/.

Ph.D. in Computer Science Program

The primary focus of the doctoral program is research, with the philosophy that students learn best by doing—beginning as apprentices and becoming junior colleagues working with faculty on scholarly research projects. The faculty in the department conduct research in all areas of computer science. The degree of Doctor of Philosophy requires a dissertation based on the candidate's original research, which is supervised by a faculty member, and all students in the Ph.D. program are actively engaged in research throughout the program. Ph.D. students spend at least half of their time on research under the direction of their faculty adviser from their first day in the program and devote themselves full time to research after coursework and other preliminaries have been completed. Ph.D. students are also expected to participate in departmental and laboratory activities full time on campus throughout the program, except possibly for summer internships elsewhere, and the department does not consider admission of part-time Ph.D. students. Further information is available at cs.columbia.edu/education/phd/.

DUAL DEGREE PROGRAM IN JOURNALISM AND COMPUTER SCIENCE

The Graduate School of Journalism and the School of Engineering and Applied Science offer a dual degree program leading to the M.S. degree in Journalism from the Graduate School of Journalism and the M.S. degree in Computer Science from the School of Engineering and Applied Science. Admitted students enroll for a total of four semesters consisting of 27 points of Computer Science coursework in which an overall 2.7 GPA must be maintained and of 37 points of Journalism coursework. In addition to taking classes already offered at the two schools, students will take Frontiers of computational journalism, a course designed specifically for the dual program. The course will teach students about the impact of digital techniques on journalism; the emerging role of citizens in the news process; the influence of social media; and the changing business models that will support newsgathering. Students will use a hands-on approach to delve deeply into information design, focusing on how to build a site, section, or application from concept to development, ensuring the editorial goals are kept uppermost in mind.

CS@CU MS BRIDGE PROGRAM IN COMPUTER SCIENCE

The CS@CU MS Bridge Program in Computer Science offers prospective applicants from noncomputer science backgrounds, including those without
programming experience, the opportunity to acquire the knowledge and skills necessary to build careers in technology. Admitted students will first take a total of seven undergraduate courses (the bridge curriculum) over two to three semesters, which will build the necessary foundation of programming and mathematical skills. There is flexibility for both scheduling and the choice of courses depending on a student’s prior experience and concurrent obligations. Students will also be closely advised during this process in order to prepare for M.S. track selection. Once the bridge is completed with an overall 3.3 GPA or higher, students are then eligible for an automatic transfer into the M.S. in Computer Science program. Further information is available at cs.columbia.edu/ms-bridge/.

COURSES IN COMPUTER SCIENCE

In the listing below, the designator COMS (Computer Science) is understood to precede all course numbers for which no designator is indicated. NOTE: Students may receive credit for only one of the following two courses: COMS W1004 and W1005. Likewise, students may receive credit for only one of the following three courses: COMS W3134, W3136, or W3137.

COMS W1005x or y Introduction to computer science and programming in MATLAB
3 pts. Lect: 3. Professor Blaer.
A general introduction to computer science concepts, algorithmic problem-solving capabilities, and programming skills in MATLAB. Assumes no prior programming background. Columbia University students may receive credit for only one of the following two courses: W1004 or W1005.

COMS W1006x and y Introduction to computer science and programming in MATLAB
3 pts. Lect: 3. Professor Blaer.
A general introduction to computer science concepts, algorithmic problem-solving capabilities, and programming skills in MATLAB. Assumes no prior programming background. Columbia University students may receive credit for only one of the following two courses: W1004 or W1005.

COMS W1007x Honors introduction to computer science
3 pts. Lect: 3. Professor Kender.
Prerequisite(s): AP Computer Science with a grade of 4 or 5 or similar experience. An honors-level introduction to computer science, intended primarily for students considering a major in computer science. Computer science as a science of abstraction. Creating models for reasoning about and solving problems. The basic elements of computers and computer programs. Implementing abstractions using data structures and algorithms. Taught in Java.

COMS W1404x and y Emerging scholars program seminar
Corequisite(s): COMS W1004/1007 or ENGI E1006. Enrollment with instructor permission only. Peer-led weekly seminar intended for first- and second-year undergraduates considering a major in computer science. Pass/fail only.

ECBM E3060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological processes viewed as mathematical operations with simulation and visualization using simple computer programming. Shares lectures with ECBM E4060, but the work requirements differ somewhat.

COMS W3101x and y Programming languages
Prerequisite(s): Fluency in at least one programming language. Introduction to a programming language. Each section is devoted to a specific language. Intended only for those who are already fluent in at least one programming language. Sections may meet for one hour per week for the whole term, for three hours per week for the first third of the term, or for two hours per week for the first six weeks. May be repeated for credit if different languages are involved.

COMS W3102x and y Development technologies
Prerequisite(s): Fluency in at least one programming language. Introduction to software development tools and environments. Each section is devoted to a specific tool or environment. One-point sections meet for two hours each week for half a semester, and two-point sections include an additional two-hour lab.

COMS W3107x Clean object-oriented design
3 pts. Lect: 3. Professor Kender.
Prerequisite(s): COMS W1004 or instructor’s permission. MAY NOT take for credit if already received credit for COMS W1007. A course in designing, documenting, coding, and testing robust computer software, according to object-oriented design patterns and clean coding practices. Taught in Java. Object-oriented design principles include: use cases; CRC; UML; javadoc; patterns (adapter, builder, command, composite, decorator, facade, factory, iterator, lazy evaluation, observer, singleton, strategy, template, visitor); design by contract; loop invariants; interfaces and inheritance hierarchies; anonymous classes and null objects; graphical widgets; events and listeners; Java’s Object class; generic types; reflection; timers, threads, and locks.

COMS W3134x and y Data structures in Java
3 pts. Lect: 3. Professor Blaer.
Prerequisite(s): COMS W1004 or knowledge of Java. Data types and structures: arrays, stacks, singly and doubly linked lists, queues, trees, sets, and graphs. Programming techniques for processing such structures: sorting and searching, hashing, garbage collection. Storage management. Rudiments of the analysis of algorithms. Taught in Java. Note: Due to significant overlap, students may receive credit for only one of the following three courses: COMS W3134, W3136, or W3137.

COMS W3136y Data structures with C/C++
4 pts. Lect: 3. Professor Lee.
Prerequisite(s): COMS W1004, W1005, W1007, or ENGI E1006. A second programming course intended for nonmajors with at least one semester of introductory programming experience. Basic elements of programming in C and C++, array-based data structures, heaps, linked lists, C programming in UNIX environment, object-oriented programming in C++, trees, graphs, generic programming, hash tables. Due
to significant overlap, students may only receive credit for either COMS W3134, W3136, or W3137.

COMS W3137y Honors data structures and algorithms
4 pts. Lect: 3. Professor Bloer.
Prerequisite(s): COMS W1004 or W1007.
Corequisite(s): COMS W3203. An honors introduction to data types and structures: arrays, stacks, singly and doubly linked lists, queues, trees, sets, and graphs. Programming techniques for processing such structures: sorting and searching, hashing, garbage collection. Storage management. Design and analysis of algorithms. Taught in Java. Note: Due to significant overlap, students may receive credit for only one of the following three courses: COMS W3134, W3136, or W3137.

COMS W3157x and y Advanced programming
Prerequisite(s): Two terms of programming experience. COMS W3134 or W3137. Recommended: Data Structures. C programming language and Unix systems programming. Also covers Git, Make, TCP/IP networking basics, C++ fundamentals.

COMS W3203x and y Discrete structures in mathematics and probability
4 pts. Lect: 3. Professor Salleb-Aouissi.
Prerequisite(s): MATH UN1102 or UN1201 or APMA E2000 and COMS W1002 or W1004 or W1007 or ENGI E1006. Logic and formal proofs, sets and relations, advanced proof techniques, number theory and modular arithmetic, graph theory, counting and basic probability, conditional probability and Bayes rule, random variables, expectation and variance, central limit theorem, probability distributions (Gaussians, binomial, and geometric).

COMS W3210x or y Scientific computation
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Two terms of calculus. Introduction to computation on digital computers. Design and analysis of numerical algorithms. Numerical solution of equations, integration, recurrences, chaos, differential equations. Introduction to Monte Carlo methods. Properties of floating point arithmetic. Applications to weather prediction, computational finance, computational science, and computational engineering.

COMS W3251x and y Computational linear algebra
4 pts. Lect: 3. Professor Dear.
Prerequisite(s): MATH UN1102 or UN1201 or APMA E2000 and COMS W1002 or W1004 or W1007 or ENGI E1006. Functions and compositions. Vectors and linear functions, matrices and linear transforms, inverses and Gaussian elimination. Vector spaces, bases, subspaces, and dimension. Inner products, norms, and orthogonal projections. Eigenvectors and eigenvalues, spectral decomposition. Quadratic forms, and singular value decomposition. Note: Previously offered for 3 points.

COMS W3261x and y Computer science theory
3 pts. Lect: 3. Professor Malkin.
Prerequisite(s): COMS W203. Corequisite(s): COMS W3134, W3136, or W3137. Regular languages: deterministic and nondeterministic finite automata, regular expressions. Context-free languages: context-free grammars, push-down automata. Turing machines, the Chomsky hierarchy, and the Church-Turing thesis. Introduction to complexity theory and NP-completeness.

COMS W3410y Computers and society
3 pts. Lect: 3. Professor Bellovin.

CSEE W3827x and y Fundamentals of computer systems
3 pts. Lect: 3. Professor Kim or Rubenstein.
Prerequisite(s): An introductory programming course. Fundamentals of computer organization and digital logic. Boolean algebra, Karnaugh maps, basic gates and components, flip-flops and latches, counters and state machines, basics of combinational and sequential digital design. Assembly language, instruction sets, ALUs, single-cycle and multi-cycle processor design, introduction to pipelined processors, caches, and virtual memory.

COMS W3902x and y Undergraduate thesis
1–6 pts. Members of the faculty.
Prerequisite(s): Agreement by faculty member to serve as thesis adviser. An independent theoretical or experimental investigation by an undergraduate major of an appropriate problem in computer science carried out under the supervision of a faculty member. A formal written report is mandatory and an oral presentation may also be required. May be taken over more than one term, in which case the grade is deferred until all 6 points have been completed. Consult the department for section assignment.

COMS W3995x or y Special topics in computer science
3 pts. Lect: 3.
Prerequisite(s): Instructor's permission. Consult the department for section assignment. Special topics arranged as the need and availability arise. Topics are usually offered on a one-time basis. Since the content of this course changes each time it is offered, it may be repeated for credit.

COMS W3998x and y Undergraduate projects in computer science
1–3 pts. Members of the faculty.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. Independent project involving laboratory work, computer programming, analytical investigation, or engineering design. May be repeated for credit, but not for a total of more than 3 points of degree credit. Consult the department for section assignment.

COMS E3999x, y or s Fieldwork
1–2 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used toward the 128-credit degree requirement. Only for SEAS computer science undergraduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation may be required. May not be used as a technical or nontechnical elective. May not be taken for pass/fail credit or audited.

ECBM E4060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Cheng.
Introduction to computational biology with emphasis on genomic data science tools and methodologies for analyzing data, such as genomic sequences, gene expression measurements and the presence of mutations. Applications of machine learning and exploratory data analysis for predicting drug response and disease progression. Latest technologies related to genomic information, such as single-cell sequencing and CRISPR, and the contributions of genomic data science to the drug development process.

COMS W4111x and y Introduction to databases
3 pts. Lect: 3. Professor Gravano.
Prerequisite(s): COMS W3134, W3136, or W3137, or instructor’s permission. Covers definition of database systems, effective design of databases, querying databases, and developing applications using databases. Includes: entity-relationship modeling, logical design of relational databases, relational algebra, SQL, database security, and an overview of query optimization and transaction processing. Additional topics: NoSQL, graph, object-relational, cloud databases, data preparation, and cleaning of real-world data. Offers both programming and non-programming homework and projects, to accommodate different programming skills and backgrounds.

COMS W4112y Database system implementation
3 pts. Lect: 2.5. Professor Ross.
Prerequisite(s): COMS W4111; fluency in Java or C++. CSEE W3827 is recommended. The principles and practice of building large-scale database management systems. Storage methods and indexing, query processing and optimization, materialized views, transaction processing and recovery, object-relational databases, parallel and distributed databases, performance considerations. Programming projects are required.

COMS W4113x Fundamentals of large-scale distributed systems
3 pts. Lect: 3. Professor Geambasu.
Prerequisite(s): COMS W3134, W3136, or W3137, COMS W3157 or good working knowledge of C and C++. COMS W4118 or CSEE W4119. Design and implementation of large-scale distributed
and cloud systems. Abstractions, design, and implementation techniques that enable the building of fast, scalable, fault-tolerant distributed systems. Topics include distributed communication models (e.g., sockets, remote procedure calls, distributed shared memory), distributed synchronization (clock synchronization, logical clocks, distributed mutexes), distributed file systems, replication, consistency models, fault tolerance, distributed transactions, agreement and commitment, Paxos-based consensus, MapReduce infrastructures, scalable distributed databases. Combines concepts and algorithms with descriptions of real-world implementations at Google, Facebook, Yahoo, Microsoft, LinkedIn etc.

**COMS W4115x and y Programming languages and translators**

3 pts. Lect: 3. Professor Edwards or Roy.
Prerequisite(s): COMS W3134, W3136, or W3137 (or equivalent), W3261, and COMS W3827, or instructor’s permission. Modern programming languages and compiler design. Imperative, object-oriented, declarative, functional, and scripting languages. Language syntax, control structures, data types, procedures and parameters, binding, scope, run-time organization, and exception handling. Implementation of language translation tools including compilers and interpreters. Lexical, syntactic, and semantic analysis; code generation; introduction to code optimization. Teams implement a language and its compiler.

**COMS W4117x or y Compilers and interpreters**

3 pts. Lect: 3. Professor Lee or Nieh.
Prerequisite(s): COMS W3115 or instructor’s permission. Continuation of COMS W4115, with broader and deeper investigation into the design and implementation of contemporary language translators, be they compilers or interpreters. Topics include parsing, semantic analysis, code generation and optimization, run-time environments, and compiler-compilers. A programming project is required.

**COMS W4118x and y Operating systems**

1 3 pts. Lect: 3. Professor Lee or Nieh.
Prerequisite(s): CSEE W3827 and knowledge of C and programming tools as covered in W3136, W3157, or W3101, or instructor’s permission. Design and implementation of operating systems. Topics include process management, process synchronization and interprocess communication, memory management, virtual memory, interrupt handling, processor scheduling, device management, I/O, and file systems. Case study of the UNIX operating system. A programming project is required.

**CSEE W4119x and y Computer networks**

Prerequisite(s): Comfort with basic probability and programming fluency in Python, C++, Java, or Ruby. Introduction to computer networks and the technical foundations of the internet, including applications, protocols, local area networks, algorithms for routing and congestion control, security, elementary performance evaluation. Several written and programming assignments required.

**CSEE W4120y Computer systems for data science**

3 pts. Lect: 3. Professor Cidon.
Prerequisite(s): Background in Computer System Organization and good working knowledge of C and C++. Corequisite(s): CSOR W4246, STAT GU4203, or equivalent approved by faculty adviser. Introduction to computer distributed systems with emphasis on warehouse scale computing systems. Topics include fundamental tradeoffs in computer systems, hardware and software techniques for exploiting instruction-level parallelism, data-level parallelism and task level parallelism, scheduling, caching, prefetching, network and memory architecture, latency and throughput optimizations, specializations, and introduction to programming data center computers.

**COMS W4130x Principles and practice of parallel programming**

3 pts. Lect: 2.5. Professor Kim.
Prerequisite(s): Experience in Java, basic understanding of analysis of algorithms. COMS W3134, W3136, or W3137 (or equivalent). Principles of parallel software design. Topics include task and data decomposition, load-balancing, reasoning about correctness, determinacy, safety, and deadlock-freedom. Application of techniques through semester-long design project implementing performant, parallel application in a modern parallel programming language.

**COMS W4140x or y Networking laboratory**

3 pts. Lect: 3. Professor Zussman.
Prerequisite(s): COMS W4119 or equivalent. Students will learn how to put “principles into practice,” in a hands-on networking lab course. The course will cover the technologies and protocols of the internet using equipment currently available to large internet service providers such as CISCO routers and end systems. A set of laboratory experiments provides hands-on experience with engineering wide-area networks and will familiarize students with the Internet Protocol (IP), Address Resolution Protocol (ARP), Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), the Domain Name System (DNS), routing protocols (RIP, OSPF, BGp), network management protocols (SNMP, and application-level protocols (FTP, TELNET, SMTP).

**COMS W4152x Engineering software as a service**

Prerequisite(s): COMS W3134, W3157, and CSEE W3827. Modern software engineering concepts and practices including topics such as Software-as-a-Service, Service-oriented Architecture, Agile Development, Behavior-driven Development, Ruby on Rails, and DevOps.

**COMS W4156x Advanced software engineering**

3 pts. Lect: 3. Professor Kaiser.
Prerequisite(s): COMS W3157 or equivalent. Software lifecycle using frameworks, libraries, and services. Major emphasis on software testing.

Centers on a team project.

**COMS W4160y Computer graphics**

3 pts. Lect: 3. Professor Reed.
Prerequisite(s): COMS W3134, W3136, or W3137; W4156 is recommended. Strong programming background and some mathematical familiarity including linear algebra is required. Introduction to computer graphics. Topics include 3D viewing and projections, geometric modeling using spline curves, graphics systems such as OpenGL, lighting and shading, and global illumination. Significant implementation is required: the final project involves writing an interactive 3D video game in OpenGL.

**COMS W4162x or y Advanced computer graphics**

Prerequisite(s): COMS W4160 or equivalent, or instructor’s permission. A second course in computer graphics covering more advanced topics including image and signal processing, geometric modeling with meshes, advanced image synthesis including ray tracing and global illumination, and other topics as time permits. Emphasis will be placed both on implementation of systems and important mathematical and geometric concepts such as Fourier analysis, mesh algorithms and subdivision, and Monte Carlo sampling for rendering. Note: Course will be taught every two years.

**COMS W4167x or y Computer animation**

3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Multivariable calculus, linear algebra, C++ programming proficiency. COMS W4156 recommended. Theory and practice of physics-based animation algorithms, including animated clothing, hair, smoke, water, collisions, impact, and kitchen sinks. Topics covered: integration of ordinary differential equations, formulation of physical models, treatment of discontinuities including collisions/contact, animation control, constrained Lagrangian Mechanics, friction/dissipation, continuum mechanics, finite elements, rigid bodies, thin shells, discretization of Navier-Stokes equations. General education requirement: quantitative and deductive reasoning (QUA).

**COMS W4170x or y User interface design**

3 pts. Lect: 3. Professor Chilton or Feiner.
Prerequisite(s): COMS W3134, W3136, or W3137. Introduction to the theory and practice of computer user interface design, emphasizing the software design of graphical user interfaces. Topics include basic interaction devices and techniques, human factors, interaction styles, dialogue design, and software infrastructure. Design and programming projects are required.

**COMS W4172y 3D user interfaces and augmented reality**

3 pts. Lect: 3. Professor Feiner.
Prerequisite(s): COMS W4160 or W4170 or instructor’s permission. Design, development, and evaluation of 3D user interfaces. Interaction techniques and metaphors, from desktop to immersive. Selection and manipulation. Travel and navigation. Symbolic, menu, gestural, and
multimodal interaction. Dialogue design. 3D software support. 3D interaction devices and displays. Virtual and augmented reality. Tangible user interfaces. Review of relevant 3D math.


ORCS E4200y Data-driven decision modeling 3 pts. Lect: 3. Professor Dear or Zhang. Introduction to modeling, estimating, and solving decision-making problems in the context of artificial intelligence and analytics. Potential topics include choice models, quantity models, online learning using multi-armed bandits, dynamic decision modeling, dynamic games, and Bayesian learning theory. Practice both theory and applications using Python programming.

COMS W4203y Graph theory 3 pts. Lect: 3. Instructor to be announced. Prerequisite(s): COMS W3203. General introduction to graph theory. Isomorphism testing, algebraic specification, symmetries, spanning trees, traversability, planarity, drawings on higher-order surfaces, colorings, extremal graphs, random graphs, graphical measurement, directed graphs, Burnside-Polya counting, voltage graph theory.

CSOR W4231x Analysis of algorithms I 3 pts. Lect: 3. Professor Yannakakis, Drinea, or Andoni. Prerequisite(s): COMS W3134, W3136 or W3137, and W3203. Introduction to the design and analysis of efficient algorithms. Topics include models of computation, efficient sorting and searching, algorithms for algebraic problems, graph algorithms, dynamic programming, probabilistic methods, approximation algorithms, and NP-completeness.

COMS W4232y Advanced algorithms 3 pts. Lect: 3. Professor Andoni. Prerequisite(s): COMS W4231. Introduces classic and modern algorithmic ideas central to many areas of Computer Science. Focus on most powerful paradigms and techniques of how to design and measure efficiency of algorithms. Broad intent, covering diverse algorithmic techniques. Covered topics are implemented and used in industry. Topics include: hashing, sketching/streaming, nearest neighbor search, graph algorithms, spectral graph theory, linear programming, models for large-scale computation, and other related topics.

COMS W4236y Introduction to computational complexity 3 pts. Lect: 3. Professor Chen. Prerequisite(s): COMS W3261. Develops a quantitative theory of the computational difficulty of problems in terms of the resources (e.g., time, space) needed to solve them. Classification of problems into complexity classes, reductions and completeness. Power and limitations of different modes of computation such as nondeterminism, randomization, interaction and parallelism.

COMS W4241y Numerical algorithms and complexity 3 pts. Lect: 3. Instructor to be announced. Prerequisite(s): Knowledge of a programming language. Some knowledge of scientific computation is desirable. Modern theory and practice of computation on digital computers. Introduction to concepts of computational complexity. Design and analysis of numerical algorithms. Applications to computational finance, computational science, and computational engineering.

STCS W4242x or y Introduction to data science 3 pts. Lect: 3. Professor Salieb-Aouissi. Practical techniques for working with large-scale data. Topics include statistical modeling and machine learning, data pipelines, programming languages, “big data” tools, and real-world topics and case studies. Statistical and data manipulation software required. Intended for nonquantitative graduate-level disciplines.

COMS W4252x or y Introduction to computational learning theory 3 pts. Lect: 3. Professor Servedio. Prerequisite(s): CSOR W4231 or COMS W4236 or W3203 and instructor’s permission or COMS W3261 and instructor’s permission. Possibilities and limitations of performing learning by computational agents. Topics include computational models of learning, polynomial time learnability, learning from examples and learning from queries to oracles. Computational and statistical limitations of learning. Applications to Boolean functions, geometric functions, automata.

COMS W4265x or y Introduction to cryptography 3 pts. Lect: 2.5. Professor Makin. Prerequisite(s): Comfort with basic discrete math and probability. Recommended: COMS W3261 or CSOR W4231. An introduction to modern cryptography, focusing on the complexity-theoretic foundations of secure computation and communication in adversarial environments; a rigorous approach, based on precise definitions and provably secure protocols. Topics include private and public key encryption schemes, digital signatures, authentication, pseudorandom generators and functions, one-way functions, trapdoor functions, number theory and computational hardness, identification and zero knowledge protocols.

COMS W4281x or y Introduction to quantum computing 3 pts. Lect: 3. Instructor to be announced. Prerequisite(s): Knowledge of linear algebra. Prior knowledge of quantum mechanics is not required although helpful. Introduction to quantum computing. Shor’s factoring algorithm, Grover’s database search algorithm, the quantum summation algorithm. Relationship between classical and quantum computing. Potential power of quantum computers.

EECS E4340x Computer hardware design 3 pts. Lect: 2. Lab: 3. Professor Sethumadhavan. Prerequisite(s): ELEN E3331 and CSEE W3827. Practical aspects of computer hardware design through the implementation, simulation, and prototyping of a PDP-8 processor. High-level and assembly languages, I/O, interrupts, datapath and control design, pipelining, busses, memory architecture. Programmable logic and hardware prototyping with FPGAs. Fundamentals of VHDL for register-transfer level design. Testing and validation of hardware. Hands-on use of industry CAD tools for simulation and synthesis.

COMS W4419x or y Internet, technology, economics, and policy 3 pts. Lect: 3. Professor Schulzrinne. Technology, economics, and policy aspects of the internet. Summarizes how the internet works technically, including protocols, standards, radio spectrum, global infrastructure and interconnection. Micro-economics with a focus on media and telecommunication economic concerns, including competition and monopolies, platforms, and behavioral economics. U.S. constitution, freedom of speech, administrative procedures act and regulatory process, universal service, role of FCC. Not a substitute for CSEE W4119. Suitable for nonmajors. May not be used as a track elective for computer science major.

COMS W4444x Programming and problem solving 3 pts. Lect: 3. Professor Ross. Prerequisite(s): COMS W3134, W3136, or W3137, and CSEE W3827. Hands-on introduction to solving open-ended computational problems. Emphasis on creativity, cooperation, and collaboration. Projects spanning a variety of areas within computer science, typically requiring the development of computer programs. Generalization of solutions to broader problems, and specialization of complex problems to make them manageable. Team-oriented projects, student presentations, and in-class participation required.
interventions using computer technology, and practices, determining the information needs of techniques for assessing current information education, and patient care. The field explores impact of such technology on medical research, limitations of biomedical informatics. Biomedical and social science. Use of computers and perspectives from medicine, computer science, the field of biomedical informatics, combining background in mathematics and receive may take this course only if they have adequate Undergraduates in their senior or junior years Prerequisite(s): Experience with computers and applications in healthcare and biomedicine 3 pts. Lect: 3. Professor Lipson. Prerequisite(s): Basic programming experience in any language. Fundamental and advanced topics in evolutionary algorithms and their application to open-ended optimization and computational design. Covers genetic algorithms, genetic programming, and evolutionary strategies, as well as governing dynamic of coevolution and symbiosis. Includes discussions of problem representations and applications to design problems in a variety of domains including software, electronics, and mechanics. ORCS E4529y Reinforcement learning 3 pts. Lect: 3. Professor Agrawal. Prerequisite(s): Probability and statistics, basic optimization (e.g., familiarity with linear and convex optimization, gradient descent, basic algorithm design constructs), familiarity with programming in Python. Markov Decision Processes (MDP) and Reinforcement Learning (RL) problems. Reinforcement Learning algorithms including Q-learning, policy gradient methods, actor-critic method. Reinforcement learning while doing exploration-exploitation dilemma, multi-armed bandit problem. Monte Carlo Tree Search methods; Distributional, Multi-agent, and Causal Reinforcement Learning.

COMS W4560x Introduction to computer applications in healthcare and biomedicine 3 pts. Lect: 3. Prerequisite(s): Experience with computers and a passing familiarity with medicine and biology. Undergraduates in their senior or junior years may take this course only if they have adequate background in mathematics and receive permission from the instructor. An overview of the field of biomedical informatics, combining perspectives from medicine, computer science, and social science. Use of computers and information in healthcare and the biomedical sciences, covering specific applications and general methods, current issues, capabilities and limitations of biomedical informatics. Biomedical Informatics studies the organization of medical information, the effective management of information using computer technology, and the impact of such technology on medical research, education, and patient care. The field explores techniques for assessing current information practices, determining the information needs of healthcare providers and patients, developing interventions using computer technology, and evaluating the impact of those interventions.

MECS E4603x Applied robotics: algorithms and software 3 pts. Lect: 3. Professor Ciocarlie. Prerequisite(s): Fundamental programming skills (e.g., COMS W1002, W1004, W1005, ENGI E1006, or equivalent). Science and systems aspects of Robotics from applied perspective, focusing on algorithms and software tools. Spatial reasoning; tools for manipulating and visualizing spatial relationships. Analysis of robotic manipulators; numerical methods for kinematic analysis. Motion planning, search-based and stochastic approaches. Applications for force and impedance control. Grading based on combination of exams and projects implemented using Robot Operating System (ROS) software framework and executed on real and simulated robotic manipulators.

COMS W4701x or y Artificial intelligence 3 pts. Lect: 3. Professor Sahle-Aouissi or Dear. Prerequisite(s): COMS W1314, W1316, or W1317 and any course on probability. Recommended: Prior knowledge of Python. Overview of Artificial Intelligence (AI) covering Search, Problem Solving, Game Playing, Knowledge Representation, Propositional logic, Predicate Calculus (first order logic), Reasoning under uncertainty, Machine Learning, and other topics in AI (including vision, natural language processing, and robotics) as time permits.

COMS W4705x Natural language processing 3 pts. Lect: 3. Professor McKeown. Prerequisite(s): COMS W1314, W1316, or W1317 (or equivalent), or instructor’s permission. Computational approaches to natural language generation and understanding. Recommended preparation: Some previous or concurrent exposure to AI or machine learning. Topics include information extraction, summarization, machine translation, dialogue systems, and emotional speech. Particular attention is given to robust techniques that can handle understanding and generation for the large amounts of text on the web or in other large corpora. Programming exercises in several of these areas.

COMS W4706y Spoken language processing 3 pts. Lect: 3. Professor Hirschberg. Prerequisite(s): COMS W1314, W1316, or W1317 (or equivalent), or instructor’s permission. Computational approaches to speech generation and understanding. Topics include speech recognition and understanding, speech analysis for computational linguistics research, and speech synthesis. Speech applications including dialogue systems, data mining, summarization, and translation. Exercises involve data analysis and building a small text-to-speech system.

COMS W4725x or y Knowledge representation and reasoning 3 pts. Lect: 3. Prerequisite(s): COMS W4701. General aspects of knowledge representation (KR). The two fundamental paradigms (semantic networks and frames) and illustrative systems. Topics include hybrid systems, time, action/plans, defaults, abduction, and case-based reasoning. Throughout the course particular attention is paid to design trade-offs between language expressiveness and reasoning complexity, and issues relating to the use of KR systems in larger applications.

COMS W4731x or y Computer vision I: first principles 3 pts. Lect: 3. Professor Nayar. Prerequisite(s): Fundamentals of calculus, linear algebra, and C programming. Students without any of these prerequisites are advised to contact the instructor prior to taking the course. Introductory course in computer vision. Topics include image formation and optics, image sensing, binary images, image processing and filtering, edge extraction and boundary detection, region growing and segmentation, pattern classification methods, brightness and reflectance, shape from shading and photometric stereo, texture, binocular stereo, optical flow and motion, 2D and 3D object representation, object recognition, vision systems and applications.

COMS W4732y Computer vision II: learning 3 pts. Lect: 3. Professor Vondrick. Prerequisite(s): COMS E4731. Fundamentals of calculus, linear algebra, and C programming. Students without any of these prerequisites are advised to contact the instructor prior to taking the course. Advanced course in computer vision. Topics include convolutional networks and back-propagation, object and action recognition, self-supervised and few-shot learning, image synthesis and generative models, object tracking, vision and language, vision and audio, 3D representation, interpretability, and bias, ethics, and media deception.

COMS W4733x or y Computational aspects of robotics 3 pts. Lect: 3. Professors Dear or Song. Prerequisite(s): COMS W1314, W1316, or W1317. Introduction to robotics from a computer science perspective. Topics include coordinate frames and kinematics, computer architectures for robotics, integration and use of sensors, world modeling systems, design and use of robotic programming languages, and applications of artificial intelligence for planning, assembly, and manipulation.

COMS W4735x or y Visual interfaces to computers 3 pts. Lect: 3. Professor Kender. Prerequisite(s): COMS W2194, W3194, or W3197. Visual input as data and for control of computer systems. Survey and analysis of architecture, algorithms, and underlying assumptions of commercial and research systems that recognize and interpret human gestures, analyze imagery such as fingerprint or iris patterns, generate natural language descriptions of medical or map imagery. Explores foundations in human psychophysics, cognitive science, and artificial intelligence.

COMS W4737x or y Biometrics 3 pts. Lect: 3. Professor Belhumeur. Prerequisite(s): A background at the sophomore level in computer science, engineering, or like discipline. We will explore the latest advances in biometrics as well as the machine learning
techniques behind them. Students will learn how these technologies work and how they are sometimes defeated. Grading will be based on homework assignments and a final project. There will be no midterm or final exam. Shares lectures with COMS E6737. Students taking COMS E6737 are required to complete additional homework problems and undertake a more rigorous final project. Students will only be allowed to earn credit for COMS W4737 or COMS E6737 but not both.

EECS E4750x or y Heterogeneous computing for signal and data processing
3 pts. Lect: 2. Professor Marianetti.
Prerequisite(s): ELEN E3801 and COMS W3134 or similar, recommended. Methods for deploying signal and data processing algorithms on contemporary general purpose graphics processing units (GPGPUs) and heterogeneous computing infrastructures. Using programming languages such as OpenCL and CUDA for computational speedup in audio, image, and video processing and computational data analysis. Significant design project.

CBMF W4761x or y Computational genomics
3 pts. Lect: 3. Professor Pe'er.
Prerequisite(s): Introductory probability and statistics and basic programming skills. Provides comprehensive introduction to computational techniques for analyzing genomic data including DNA, RNA and protein structures; microarrays; transcription and regulation; regulatory, metabolic and protein interaction networks. The course covers sequence analysis algorithms, dynamic programming, hidden Markov models, phylogenetic analysis, Bayesian network techniques, neural networks, clustering algorithms, support vector machines, Boolean models of regulatory networks, flux based analysis of metabolic networks and scale-free network models. The course provides self-contained introduction to relevant biological mechanisms and methods.

COMS W4762x Machine learning for functional genomics
3 pts. Lect: 3. Professor Knowles.
Prerequisite(s): Proficiency in a high-level programming language (Python/R/Julia). Recommended: introductory machine learning class (such as COMS W4771). Introduces modern probabilistic machine learning methods using applications in data analysis tasks from functional genomics, where massively-parallel sequencing is used to measure the state of cells, e.g., what genes are being expressed, what regions of DNA ("chromatin") are active ("open") or bound by specific proteins.

COMS W4771y Machine learning
3 pts. Lect: 3. Professor Hsu or Verma.
Prerequisite(s): Any introductory course in linear algebra and any introductory course in statistics are both required. Highly recommended: COMS W4701 or knowledge of artificial intelligence. Topics from generative and discriminative machine learning including least squares methods, support vector machines, kernel methods, neural networks, Gaussian distributions, linear classification, linear regression, maximum likelihood, exponential family distributions, Bayesian networks, Bayesian inference, mixture models, the EM algorithm, graphical models and hidden Markov models. Algorithms implemented in MATLAB.

COMS W4772x Advanced machine learning
3 pts. Lect: 3. Professor Hsu.
Prerequisite(s): COMS W4771 or instructor's permission; knowledge of linear algebra and introductory probability or statistics is required. An exploration of advanced machine learning tools for perception and behavior learning. How can machines perceive, learn from, and classify human activity computationally? Topics include appearance-based models, principal and independent components analysis, dimensionality reduction, kernel methods, manifold learning, latent models, regression, classification, Bayesian methods, maximum entropy methods, real-time tracking, extended Kalman filters, time series prediction, hidden Markov models, factorial HMMs, input-output HMMs, Markov random fields, variational methods, dynamic Bayesian networks, and Gaussian/Dirichlet processes. Links to cognitive science.

COMS W4773y Machine learning theory
3 pts. Lect: 3. Professor Hsu.
Prerequisite(s): COMS W4771. Theoretical study of algorithms for machine learning and high-dimensional data analysis. Topics include high-dimensional probability, theory of generalization and statistical learning, online learning and optimization, spectral analysis.

COMS W4774y Unsupervised learning
3 pts. Lect: 3. Professor Verma.
Prerequisite(s): COMS W4771 and background in probability and statistics, linear algebra, and multivariate calculus. Ability to program in a high-level language, and familiarity with basic algorithm design and coding principles. Core topics from unsupervised learning such as clustering, dimensionality reduction and density estimation. Topics in clustering: k-means clustering, hierarchical clustering, spectral clustering, clustering with various forms of feedback, good initialization techniques and convergence analysis of various clustering procedures. Topics in dimensionality reductions: linear techniques such as PCA, ICA, Factor Analysis, Random Projections, non-linear techniques such as LLE, ISOMap, Laplacian Eigenmaps, ISNE, and study of embeddings of general metric spaces, what sorts of theoretical guarantees can one provide about such techniques. Miscellaneous topics: design and analysis of data structures for fast Nearest Neighbor search such as Cover Trees and LSH. Algorithms will be implemented in either MATLAB or Python.

COMS W4775y Causal inference
3 pts. Lect: 3. Professor Bareinboim.
Prerequisite(s): Discrete Math, Calculus, Statistics (basic probability, modeling, experimental design), some programming experience. Causal Inference theory and applications. Theoretical topics include 3-layer causal hierarchy, causal bayesian networks, structural learning, identification problem and do-calculus, linear identifiability, bounding, and counterfactual analysis. Applied topics include intersection with statistics, empirical-data sciences (social and health), and AI and ML.

COMS W4776x Machine learning for data science
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): IEOR E4150 or STAT GU4001 or equivalent, COMS W3251 or equivalent. Introduction to machine learning, emphasis on data science. Topics include least square methods, Gaussian distributions, linear classification, linear regression, maximum likelihood, exponential family distributions, Bayesian networks, Bayesian inference, mixture models, the EM algorithm, graphical models, hidden Markov models, support vector machines kernel methods. Emphasizes methods and problems relevant to big data. Students may not receive credit for both COMS W4771 and W4776.

CSEE W4823x or y Advanced logic design
3 pts. Lect: 3. Professor Nowick.
Prerequisite(s): CSEE W3827, or a half-semester introduction to digital logic, or equivalent. An introduction to modern digital system design. Advanced topics in digital logic: controller synthesis (Mealy and Moore machines); adders and multipliers; structured logic blocks (PLDs, PALs, ROMs); iterative circuits. Modern design methodology: register transfer level modeling (RTL); algorithmic state machines (ASM); introduction to hardware description languages (VHDL or Verilog); system-level modeling and simulation; design examples.

CSEE W4824x Computer architecture
3 pts. Lect: 3. Professor Sethumadhavan.

CSEE W4840y Embedded systems
Prerequisite(s): CSEE W4823. Embedded system design and implementation combining hardware and software. I/O, interfacing, and peripherals. Weekly laboratory sessions and term project on design of a microprocessor-based embedded system including at least one custom peripheral. Knowledge of C programming and digital logic required. Lab required.

CSEE E4860x or y System-on-chip platforms
3 pts. Lect: 3. Professor Carloni.
Prerequisite(s): COMS W3157 and CSEE W3827 Design and programming of System-on-Chip (SoC) platforms. Topics include overview of
technology and economic trends, methodologies and supporting CAD tools for system-level design; models of computation, the SystemC language, transaction-level modeling, hardware-software partitioning, high-level synthesis, system programming, on-chip communication, memory organization, power management and optimization, integration of programmable processor cores and specialized accelerators. Case studies of modern SoC platforms for various classes of applications.

**COMS W4901x and y Projects in computer science**
1–3 pts. Members of the faculty.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. A second-level independent project involving laboratory work, computer programming, analytical investigation, or engineering design. May be repeated for credit, but not for a total of more than 3 points of degree credit. Consult the department for section assignment.

**COMS W4995x or y Special topics in computer science, I**
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Instructor’s permission. Special topics arranged as the need and availability arises. Topics are usually offered on a one-time basis. Since the content of this course changes each time it is offered, it may be repeated for credit. Consult the department for section assignment.

**COMS W4996x or y Special topics in computer science, II**
3 pts. Lect: 3.
Prerequisite(s): Instructor’s permission. A continuation of COMS W4995 when the special topic extends over two terms.

**COMS E611x Advanced database systems**
3 pts. Lect: 2. Professor Gravano.
Prerequisite(s): COMS W4111 and knowledge of Java or instructor’s permission. Continuation of COMS W4111, covers latest trends in both database research and industry: information retrieval, web search, data mining, data warehousing, OLAP, decision support, multimedia databases, and XML and databases. Programming projects required.

**COMS E611y Topics In database systems**
3 pts. Lect: 2.
Prerequisite(s): COMS W4111. Concentration on some database paradigm, such as deductive, heterogeneous, or object-oriented, and/or some database issue, such as data modeling, distribution, query processing, semantics, or transaction management. A substantial project is typically required. May be repeated for credit with instructor’s permission.

**COMS E614x Advanced distributed systems**
Prerequisite(s): COMS W4113 and W4118. Reviews influential research that provides the basis of most large-scale, cloud infrastructures today. Students read, present, and discuss papers. Topics include distributed consensus, consistency models and algorithms, service-oriented architectures, large-scale data storage, distributed transactions, big-data processing frameworks, distributed systems security. Reviews established results and state-of-the-art research.

**COMS E617x or y Topics in programming languages and translators**
3 pts. Lect: 2.
Prerequisite(s): COMS W4115 or instructor’s permission. Concentration on the design and implementation of programming languages, and tools focused on advanced applications in new areas in software verification, distributed systems, programming in the large, and web computing. A substantial project is typically required. May be repeated for credit.

**COMS E6118y Operating systems, II**
3 pts. Lect: 2. Professor Nieh.
Prerequisite(s): COMS W4118. Corequisite(s): CSEE W4119. Continuation of COMS W4118, with emphasis on distributed operating systems. Topics include interfaces to network protocols, distributed run-time binding, advanced virtual memory issues, advanced means of interprocess communication, file system design, design for extensibility, security in a distributed environment. Investigation is deeper and more hands-on than in COMS W4118. A programming project is required.

**COMS E6121x Reliable software**
Prerequisite(s): at least one of COMS W4118, W4115, or W4117, or significant software development experiences. Topics include automated debugging, automated software repair, concurrent software reliability, software error detection, and more.

**COMS E6123x or y Programming environments and software tools (PEST)**
Prerequisite(s): COMS W4156 or equivalent. Software methodologies and technologies concerned with development and operation of today’s software systems. Reliability, security, systems management and societal issues. Emerging software architectures such as enterprise and grid computing. Term paper and programming project. Seminar focus changes frequently to remain timely.

**COMS E6124x Hardware security**
3 pts. Lect: 3. Professor Sethumadhavan.
Prerequisite(s): CSEE W3827 and COMS W3157. Recommended: CSEE W4824 and COMS W4187. Techniques for securing the foundational aspects of all computing devices and systems. Topics include: hardware-up security, hardware supply chain trust and security, storing secrets in hardware, boot time trust and security, side channel attacks and defenses, hardware support for compartmentalization, fault attacks and defenses, hardware support to strengthen software: memory safety, control flow integrity, information flow tracking, diversity, obfuscation, anomaly detection. Hardware support for accelerating cryptography and applied cryptography.

**COMS E6125y Web-enhanced information management (WHIM)**
Prerequisite(s): At least one COMS W41xx or COMS E61xx course and/or COMS W4444, or instructor’s permission. Strongly recommended: COMS W4111. History of hypertext, markup languages, groupware and the web. Evolving web protocols, formats and computation paradigms such as HTTP, XML and Web Services. Novel application domains enabled by the web and societal issues. Term paper and programming project. Seminar focus changes frequently to remain timely.

**COMS E6156y Topics in software engineering**
Topics in software engineering arranged as the need and availability arises, usually offered on a one-time basis. Since the content of this course changes, it may be repeated for credit with instructor approval. Consult the department for section assignment. Software methodologies and technologies concerned with development and operation of today’s software systems. Reliability, security, privacy, sustainability, and societal issues. Emerging software architectures such as microservices, serverless, and deep learning. Term paper and programming project.

**COMS E6160x or y Topics in computer graphics**
3 pts. Lect: 2. Professor Bellhomme.
Prerequisite(s): COMS W4160 or instructor’s permission. An advanced graduate course, involving study of an advanced research topic in Computer Graphics. Content varies between offerings, and the course may be repeated for credit. Recent offerings have included appearance models in graphics, and high quality real-time rendering.

**COMS E6174y Interaction design: a perceptual approach**
3 pts. Lect: 3.
Prerequisite(s): COMS W4170 or instructor’s permission. Design methodology for special-purpose user interfaces. Emphasis on how psychology and perception inform good design. Interviewing and task modeling, participatory design, and low-fidelity prototyping. Applications of brain research, graphic design and art to develop custom user interfaces components, screen layouts, and interaction techniques for application-specific systems.

**COMS E6176x or y User interfaces for mobile and wearable computing**
Prerequisite(s): COMS W4170 or instructor’s permission. Introduction to research on user interfaces for mobile and wearable computing through lectures, invited talks, student-led discussions of important papers, and programming projects. Designing and authoring for mobility and wearability. Ubiquitous/pervasive computing. Collaboration with other users. Display, interaction, and communication technologies. Sensors for tracking position, orientation, motion, environmental context, and personal context.
Applications and social consequences.

COMS E6178y Human–computer interaction seminar
3 pts. Lect: 2.5. Professor Smith.
Prerequisite(s): COMS W4170. Human–computer interaction (HCI) studies (1) what computers are used for, (2) how people interact with computers, and (3) how either of those should change in the future. Topics include ubiquitous computing, mobile health, interaction techniques, social computing, mixed reality, accessibility, and ethics. Activities include readings, presentations, and discussions of research papers. Substantial HCI research project required.

CSEE E6180x or y Modeling and performance
Prerequisite(s): COMS W4118 and STAT GU4001. Introduction to queuing analysis and simulation techniques. Evaluation of time-sharing and multiprocessor systems. Topics include priority queuing, buffer storage, and disk access, interference and bus contention problems, and modeling of program behaviors.

COMS E6181x or y Advanced internet services
3 pts. Lect: 2. Professor Schulzrinne.
In-depth survey of protocols and algorithms needed to transport multimedia information across the internet, including audio and video encoding, multicast, quality-of-service, voice-over IP, streaming media and peer-to-peer multimedia systems. Includes a semester-long programming project.

COMS E6183x or y Advanced topics in network security
3 pts. Lect: 3. Professor Jana.
Prerequisite(s): COMS W4180, CSEE W4119 and COMS W4261 recommended. Review the fundamental aspects of security, including authentication, authorization, access control, confidentiality, privacy, integrity, and availability. Review security techniques and tools, and their applications in various problem areas. Study the state of the art in research. A programming project is required.

COMS E6184y Seminar on anonymity and privacy
3 pts. Lect: 3.
Prerequisite(s): COMS W4261 or W4180 or CSEE W4119 or instructor’s permission. Covers the following topics: Legal and social framework for privacy. Data mining and databases. Anonymous commerce and internet usage. Traffic analysis. Policy and national security considerations. Classes are seminars with students presenting papers and discussing them. Seminar focus changes frequently to remain timely.

COMS E6185x or y Intrusion and anomaly detection systems
3 pts. Lect: 2. Professor Stolfo.
Pre- or corequisite: COMS W4180 Network security. The state of threats against computers, and networked systems. An overview of computer security solutions and why they fail. Provides a detailed treatment for network and host-based intrusion detection and intrusion prevention systems. Considerable depth is provided on anomaly detection systems to detect new attacks. Covers issues and problems in e-mail (spam, and viruses) and insider attacks (masquerading and impersonation).

COMS E6232x or y Analysis of algorithms, II
3 pts. Lect: 2.
Prerequisite(s): CSOR W4231. Continuation of CSOR W4231.

COMS E6253y Advanced topics in computational learning theory
3 pts. Lect: 3. Professor Servedio.
Prerequisite(s): CSOR W4231 or equivalent; COMS W4252 or W4236 helpful but not required. In-depth study of inherent abilities and limitations of computationally efficient learning algorithms. Algorithms for learning rich Boolean function classes in online, Probably Approximately Correct, and exact learning models. Connections with computational complexity theory emphasized. Substantial course project or term paper required.

COMS E6261x or y Advanced cryptography
3 pts. Lect: 3. Professor Malkin.
Prerequisite(s): COMS W4261. A study of advanced cryptographic research topics such as: secure computation, zero knowledge, privacy, anonymity, cryptographic protocols. Concentration on theoretical foundations, rigorous approach, and provable security. Content varies between offerings. May be repeated for credit.

COMS E6291x or y Theoretical topics in computer science
3 pts. Lect: 3. Professor Servedio.
Prerequisite(s): Instructor’s permission. Concentration on some theoretical aspect of computer science. Content varies from year to year. May be repeated for credit.

EECS E6320y Advanced digital electronic circuits
3 pts. Lect: 2. Professor Seok.
Prerequisite(s): EECS E4321. Advanced topics in the design of digital integrated circuits. Clocking and nonclocked combinational logic styles. Timing circuits: latches and flip-flops, phase-locked loops, delay-locked loops. SRAM and DRAM memory circuits. Modeling and analysis of on-chip interconnect. Power distribution and power-supply noise. Clocking, timing, and synchronization issues. Circuits for chip-to-chip electrical communication. Advanced technology issues that affect circuit design. The class may include a team circuit design project.

COMS E6424x Hardware security
3 pts. Lect: 2. Professor Sethumadhavan.
Prerequisite(s): CSEE W3827 and COMS W3157; Recommended: CSEE W4824 and COMS W4187. Techniques for securing the foundational aspects of all computing devices and systems. Topics include hardware-up security, hardware supply chain and trust and security, storing secrets in hardware, boot time trust and security, side channel attacks and defenses, hardware support for compartmentalization, fault attacks and defenses, hardware support to strengthen software: memory safety, control flow integrity, security policies, and software for trustworthiness.

CSEE W6600x or y From data to solutions
3 pts. Lect: 3. Professor Hirschberg or Chang.
Prerequisite(s): Familiarity with common data science methods and tools. Must be able to write coherent weekly summary. Intended for students interested in data science and interdisciplinary research. Covers problems in medical research, journalism, history, economics, business, English, psychology, and other areas amenable to computational approaches.

EECS E6690-6699x or y Topics in data driven analysis and computation
Prerequisite(s): the instructor’s permission. Selected advanced topics in data-driven analysis and computation. Content varies from year to year, and different topics rotate through the course numbers 6690 to 6699.

STCS GU6701x or y Foundations of graphical models
3 pts. Lect: 3. Professor Blei.
Prerequisite(s): Basic probability and statistics, calculus, and some optimization. Ability to write software to analyze data. Knowledge of programming language for statistics and machine learning, such as R or Python. PhD-level course on development and use of probability models. Covers mathematical properties, algorithms, and their application to real problems. In-depth understanding of cutting-edge modern probabilistic modeling. Weekly papers, assignments, and final project required.

COMS E6731y Humanoid robots
Prerequisite(s): A course in at least one of the following: AI, robotics, computer graphics, or computer vision. Seminar on humanoid robots. Analysis of existing hardware and software platforms. Programming of multi-degree-of-freedom robots. Understanding sensor feedback in perceive-act-sense control paradigms. Task-level planning and reasoning. Final project includes implementing a humanoid robot task on either a simulated or physical robot.

COMS E6732x or y Computational imaging
3 pts. Lect: 3. Professor Nayar.
Prerequisite(s): COMS W4731 or instructor’s permission. Computational imaging uses a combination of novel imaging optics and a computational module to produce new forms of visual information. Survey of the state-of-the-art in computational imaging. Review of recent papers on omnidirectional and panoramic imaging, caladiophic imaging, high dynamic range imaging, mosaicing and superresolution. Classes are seminars with the instructor, guest speakers, and students presenting papers and discussing them.

COMS E6733x or y 3D photography
Prerequisite(s): Experience with at least one
of the following topics: Computer graphics, computer vision, pixel processing, robotics or computer-aided design, or instructor's permission. Programming proficiency in C, C++, or JAVA.

3D Photography—the process of automatically creating 3D, texture-mapped models of objects in detail. Applications include robotics, medicine, graphics, virtual reality, entertainment and digital movies etc. Topics include 3D data acquisition devices, 3D modeling systems and algorithms to acquire, create, augment, manipulate, render, animate and physically build such models.

COMS E6734y Computational photography
3 pts. Lect: 3. Professor Belhumeur.
Prerequisite(s): COMS W4160, W4731, or a working knowledge of photography are recommended. Students should have knowledge in any of three core areas: computer vision, computer graphics, or photography. Computational techniques are used to produce a new level of images and visual representations. Topics include HDR imaging, feature matching using RANSAC, image mosaics, image-based rendering, motion magnification, camera lens arrays, programmable lighting, face detection, single and multiview geometry, and more.

COMS E6735y Visual databases
3 pts. Lect: 3. Professor Kender.
Prerequisite(s): COMS W3134, W3136, or W3137 (or equivalent). COMS W4731 and W4735 helpful but not required. Contact instructor if uncertain. The analysis and retrieval of large collections of image and video data, with emphasis on visual semantics, human psychology, and user interfaces. Low-level processing: features and similarity measures; shot detection; key frame selection; machine learning methods for classification. Middle-level processing: organizational rules for videos, including unedited (home, educational), semi-edited (sports, talk shows), edited (news, drama); human memory limits; progressive refinement; visualization techniques; incorporation of audio and text. High-level processing: extraction of thematic structures; ontologies; semantic filters, and learning; personalization of summaries and interfaces; detection of pacing and emotions. Examples and demonstrations from commercial and research systems throughout. Substantial course project or term paper required.

COMS E6737x or y Biometrics
3 pts. Lect: 3. Professor Belhumeur.
Prerequisite(s): Background at the sophomore level in computer science, engineering, or like discipline. Corequisites: None. We will explore the latest advances in biometrics as well as the machine learning techniques behind them. Students will learn how these technologies work and how they are sometimes defeated. Grading will be based on homework assignments and a final project. There will be no midterm or final exam. Shares lectures with COMS W4737. Students taking COMS E6737 are required to complete additional homework problems and undertake a more rigorous final project. Students will only be allowed to earn credit for COMS W4737 or COMS E6737 but not both.

CSE E6824y Parallel computer architecture
3 pts. Lect: 2. Professor Sethumadhavan.
Prerequisite(s): CSE W4824. Parallel computer principles, machine organization and design of parallel systems including parallelism detection methods, synchronization, data coherence and interconnection networks. Performance analysis and special purpose parallel machines.

CSE E6847y Distributed embedded systems
3 pts. Lect: 2.
Prerequisite(s): Any COMS W411X, CSE W48XX, or ELEN E43XX course, or instructor's permission. An interdisciplinary graduate-level seminar on the design of distributed embedded systems. System robustness in the presence of highly variable communication delays and heterogeneous component behavior. The study of the enabling technologies (VLSI circuits, communication protocols, embedded processors, RTOSs), models of computation, and design methods. The analysis of modern domain-specific applications including on-chip micro-networks, multiprocessor systems, fault-tolerant architectures, and robust deployment of embedded software. Research challenges such as design complexity, reliability, scalability, safety, and security. The course requires substantial reading, class participation and a research project.

CSE E6861y Computer-aided design of digital systems
Prerequisite(s): (i) one semester of advanced digital logic (CSE W4823 or equivalent, or instructor’s permission); and (ii) a basic course in data structures and algorithms COMS W3134, W3136, W3137, W3157, or equivalent, and familiarity with programming. Introduction to modern digital CAD synthesis and optimization techniques. Topics include modern digital system design (high-level synthesis, register-transfer level modeling, algorithmic state machines, optimal scheduling algorithms, resource allocation and binding, retiming), controller synthesis and optimization, exact and heuristic two-level logic minimization, optimal technology mapping to library cells (for delay, power and area minimization), advanced data structures (binary decision diagrams), SAT solvers and their applications, static timing analysis, and introduction to testability. Includes hands-on small design projects using and creating CAD tools.

CSE E6863x Formal verification of hardware and software systems
3 pts. Lect: 2. Professor Theobald or Ivanic.
Prerequisite(s): COMS W3134, W3136, or W3137 and COMS W3261. Introduction to the theory and practice of formal methods for the design and analysis of correct (i.e., bug-free) concurrent and embedded hardware/software systems. Topics include temporal logics; model checking; deadlock and liveliness issues; fairness; satisfiability (SAT) checkers; binary decision diagrams (BDDs); abstraction techniques; introduction to commercial formal verification tools. Industrial state-of-the-art, case studies, and experiences: software analysis (C/C++/Java), hardware verification (RTL).

CSE E6868x or y Embedded scalable platforms
3 pts. Lect: 2. Professor Carloni.
Prerequisite(s): CSE W4868 or instructor’s permission. Interdisciplinary graduate-level seminar on design and programming of embedded scalable platforms. Content varies between offerings to cover timely relevant issues and latest advances in system-on-chip design, embedded software programming, and electronic design automation. Requires substantial reading of research papers, class participation, and semester-long project.

EECS E6870x or y Speech recognition
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Basic probability and statistics. Theory and practice of contemporary automatic speech recognition. Gaussian mixture distributions, hidden Markov models, pronunciation modeling, decision trees, finite-state transducers, and language modeling. Selected advanced topics will be covered in more depth.

COMS E6900x and y Tutorial in computer science
1–3 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. A reading course in an advanced topic for a small number of students, under faculty supervision.

COMS E6901x Projects in computer science
1–12 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Software or hardware projects in computer science. Before registering, the student must submit a written proposal to the instructor for review. The proposal should give a brief outline of the project, estimated schedule of completion, and computer resources needed. Oral and written reports are required. May be taken over more than one semester, in which case the grade will be deferred until all 12 points have been completed. No more than 12 points of COMS E6901 may be taken. Consult the department for section assignment.

COMS E6902x and y Thesis
1–9 pts. Members of the faculty.
Available to M.S. candidates. An independent investigation of an appropriate problem in computer science carried out under the supervision of a faculty member. A formal written report is essential and an oral presentation may also be required. May be taken over more than one semester, in which case the grade will be deferred until all 9 points have been completed. No more than 9 points of COMS E6902 may be taken. Consult the department for section assignment.

COMS E6910x and y Fieldwork
1 pt. Members of the faculty.
Prerequisite(s): Obtained internship and approval from faculty adviser. Only for M.S. students in the Computer Science Department who need relevant work experience as part of their program of study.
Final report required. May not be taken for pass/fail credit or audited.

COMS E6915y Technical writing for computer scientists and engineers
1 pt. Members of the faculty.
Available to M.S. or Ph.D. candidates in CS/CE. Topics to help CS/CE graduate students’ communication skills. Emphasis on writing, presenting clear, concise proposals, journal articles, conference papers, theses, and technical presentations. May be repeated for credit. Credit may not be used to satisfy degree requirements.

COMS E6998x and y Topics in computer science
3 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Selected topics in computer science. Content varies from year to year. May be repeated for credit.

COMS E6999x and y Topics in computer science, II
3 pts.
Prerequisite(s): COMS E6998. Continuation of COMS E6998.

COMS E9800x and y Directed research in computer science
1–15 pts. Members of the faculty.
Prerequisite(s): Submission of outline of proposed research for approval by faculty member who will supervise. The department must approve the number of points. May be repeated for credit. Only for Eng.Sc.D. candidates.

COMS E9910x and y Graduate research, I
1–6 pts. Members of the faculty.
Prerequisite(s): Submission of an outline of the proposed research for approval by the faculty member who will supervise. The department must approve the number of credits. May be repeated for credit. Only for M.S. candidates holding GRA or TA appointments. Note: It is NOT required that a student take Graduate research, I prior to taking Graduate research, II. Consult the department for section assignment.

COMS E9911x and y Graduate research, II
1-15 pts. Members of the faculty.
Prerequisite(s): Submission of an outline of the proposed research for approval by the faculty member who will supervise. The department must approve the number of points. May be repeated for credit. Only for M.S./Ph.D. track and Ph.D. students. Note: It is NOT required that a student take Graduate research, I prior to taking Graduate research, II. Consult the department for section assignment.
EARTH RESOURCES AND THE ENVIRONMENT

The Earth and Environmental Engineering program fosters education and research in the development and application of technology for the sustainable development, use, and integrated management of Earth's resources. Resources are identified as minerals, energy, water, air, and land, as well as the physical, chemical, and biological components of the environment. There is close collaboration with other engineering disciplines, the Lamont-Doherty Earth Observatory, the International Research Institute for Climate Prediction, the Center for Environmental Research and Conservation, and other Columbia Earth Institute units.

THE HENRY KRUMB SCHOOL OF MINES AT COLUMBIA UNIVERSITY

The department is the direct lineage of the School of Mines of Columbia University, which was the first mining and metallurgy school in the U.S. (1864). It became the foundation for Columbia's School of Engineering and Applied Science and later the home of the Department of Mining, Metallurgical and Mineral Engineering. However, the title "School of Mines" was retained by Columbia University honoris causa. You can see the bronze statue of The Metallurgist (Le Marteleur) in front of Columbia's Mudd Hall that was named after an alumnus of the School of Mines.

One century after its formation, the School of Mines was renamed Henry Krumb School of Mines (HKSM) in honor of the generous alumnus of the School of Mines and his wife, Lavon Duddleson Krumb. HKSM has been a leader in mining and metallurgy research and education, including the first mining handbook by Professor Peel, the first mineral processing handbook by Professor Taggart, and other pioneering work in mineral benefaction, chemical thermodynamics, kinetics, transport phenomena in mineral extraction and processing, ecological and environmentally responsible mining, and pursuit of state-of-the-art research advancing responsible use of Earth's resources. The Henry Krumb School of Mines located in The Fu Foundation School of Engineering and Applied Science offers students interested in mining and metallurgy the opportunity to focus their studies in these fields within the department of Earth and Environmental Engineering.

In 1986, HKSM was designated by Governor Cuomo as the mining and Mineral Resources Research Institute of the State of New York.

EARTH AND ENVIRONMENTAL ENGINEERING (EEE)

With the creation of the Earth Institute at Columbia University, a major initiative in the study of Earth, its environment and society, the traditional programs of HKSM in mining, mineral processing, and extractive metallurgy were expanded in the late nineties to encompass environmental concerns related to the use of materials, energy and water resources, and to reflect one of nine departments of SEAS with a focus on the development and application of technology for the sustainable development, use and integrated management of Earth’s resources.

As a result of the vast developments in the technologies and fields of environmental management, in 1996 and 1998, respectively, the engineering school created the M.S. program in Earth Resources Engineering and the
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<th>SEMESTER I</th>
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<tr>
<td><strong>MATHEMATICS</strong></td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0)</td>
<td>APMA E2101 (3)</td>
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<td>or MATH UN1207 (4)</td>
<td>MATH UN1208 (4)</td>
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<td>MATH UN2030 (3) ODE</td>
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<td>UN1402 (3)</td>
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<td>CIEE E4252 (3)</td>
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<td>or UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
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<td>Environmental engineering</td>
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<td></td>
<td>or UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
<td>CHEM UN2443 (3.5) or PHYS UN1403 (3) or PHYS UN2601 (3.5) or BIOL UN2005 (4)</td>
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<td><strong>CHEMISTRY</strong></td>
<td>UN1403 (3.5) and Lab UN1500 (3) either semester</td>
<td>UN1404 (3.5)</td>
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<td>or UN1604 (3.5)</td>
<td>UN1507 (3)</td>
<td>HUMA CC1001, COCI CC1101, or Global Core (3–4)</td>
<td>ECON UN1105 (4) and UN1155 recitation (0)</td>
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<td>or UN2045 (3.5)</td>
<td>UN2046 (3.5) and Lab UN1507 (3)</td>
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<td>HUMA UN1121 or UN1123 (3)</td>
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<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
<td>ENGL CC1010 (3)</td>
<td>HUMA CC1001, COCI CC1101, or Global Core (3–4)</td>
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<tr>
<td><strong>REQUIRED PROFESSIONAL AND TECHNICAL ELECTIVES</strong></td>
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<td>EEE E1100 (3)</td>
<td>STAT GU4001 (3)</td>
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<td>A better planet by design</td>
<td>EEE E2100 (3)</td>
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<tr>
<td><strong>COMPUTER SCIENCE</strong></td>
<td>ENGI E1006 (3) any semester</td>
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<tr>
<td><strong>PHYSICAL EDUCATION</strong></td>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
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<tr>
<td><strong>THE ART OF ENGINEERING</strong></td>
<td>ENGI E1102 (4) either semester</td>
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</table>
B.S. program in Earth and Environmental Engineering to meet the needs of a changed society. Students interested in the traditional disciplines of mining, mineral engineering and metallurgy continue to study these fields through the Earth and Environmental Engineering department course offerings as well as the course offerings through the Material Science and Engineering program.

The B.S. program in Earth and Environmental Engineering was initiated in the fall of 1998 to replace the mining/mineral/extractive metallurgy programs of HKSM and is now accredited by ABET.

The department builds upon this legacy every year through its core class and unofficial motto, “A Better Planet By Design,” bringing together:

- water conservation, allocation, and decontamination
- climate change mitigation
- minerals, metals, and materials processing, extraction, and reuse
- waste and pollution prevention, mitigation and management
- renewable energy and carbon management

By bridging engineering scales from colloidal interfaces to resource distribution, the department now considers resource development both on Earth and off, with a new effort in space mining.

The EEE program warmly welcomes Combined Plan students. An EEE minor is offered to all Columbia engineering students who wish to enrich their academic record by concentrating some of their technical electives on Earth/Environment subjects.

**RESEARCH CENTERS ASSOCIATED WITH EARTH AND ENVIRONMENTAL ENGINEERING**

- Center for Advanced Materials for Energy and Environment. The Center develops advanced materials to address challenges for closing the energy loop, carbon loop, and water loop.
- Center for Life Cycle Analysis (CLCA). The Center for Life Cycle Analysis (CLCA) provides a framework for quantifying the potential environmental impacts of material and energy inputs and outputs of a process or product from “cradle to grave.” For more information: clca.columbia.edu.
- Columbia Climate School. For more information: climate.columbia.edu.

**EARTH AND ENVIRONMENTAL ENGINEERING: THIRD AND FOURTH YEARS**

<table>
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<tr>
<th>REQUIRED COURSES</th>
<th>SEMESTER V</th>
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<th>SEMESTER VII</th>
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<tr>
<td></td>
<td>EAEE E3103 (3) Energy, minerals, and material systems</td>
<td>EAEE E4003 (3) Aquatic chemistry</td>
<td>EAEE E3998 (2) Undergraduate design project</td>
<td>CIEE E3255 (3) Environmental control and pollution reduction systems</td>
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- EAEE E3200 (3) Applied transport and chemical rate phenomena
- CIEE E3250 (3) Hydrosystems engineering

- CHEE E3010 (3) Principles of chemical engineering thermodynamics

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<tr>
<th>TECHNICAL ELECTIVES</th>
<th>3 points</th>
<th>6 points</th>
<th>9 points</th>
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<tr>
<td>NONTECHNICAL ELECTIVES</td>
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<td>3 points</td>
<td>6 points</td>
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<tr>
<td>TOTAL POINTS</td>
<td>12</td>
<td>16</td>
<td>14</td>
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1 For class of 2023, EAEE E3800 and E3801 are required.
Columbia Water Center. The Center was established in 2008 to address issues of Global Water Security. For more information: water.columbia.edu.


Industry/University Cooperative Research Center for Particulate and Surfactant Systems (CPaSS). The goals of CPaSS are to perform industrially relevant research to address the technological needs in commercial surfactant and polymer systems, develop new and more efficient surface-active reagents for specific applications in the industry and methodologies for optimizing their performance, promote the use of environmentally benign surfactants in a wide array of technological processes, and build a resource center to perform and provide state-of-the-art facilities for characterization of surface-active reagents. For more information: blogs.cuit.columbia.edu/iucrc/.

Langmuir Center for Colloids and Interfaces (LCCI). This center brings together experts from mineral engineering, applied chemistry, chemical engineering, biological sciences, and chemistry to probe complex interactions of colloids and interfaces with surfactants and macromolecules.

Lamont-Doherty Earth Observatory (LDEO). For more information: ldeo.columbia.edu.

Lenfest Center for Sustainable Energy (LCSE). The mission of the Lenfest Center for Sustainable Energy is to advance science and develop innovative technologies that provide sustainable energy for all humanity while maintaining the stability of Earth’s natural systems. For more information: energy.columbia.edu.

The Earth Institute. For more information: earth.columbia.edu.

SCHOLARSHIPS, FELLOWSHIPS, AND INTERNSHIPS
The department arranges for undergraduate summer internships after the sophomore and junior years. Undergraduates can also participate in graduate research projects under the work-study program. Graduate research and teaching assistantships, as well as fellowships funded by the Department, are available to qualified graduate students. GRE scores are required of all applicants for graduate studies.

UNDERGRADUATE PROGRAM
The Bachelor of Science (B.S.) degree in Earth and Environmental Engineering prepares students for careers in the public and private sector concerned with primary materials (minerals, fuels, water) and the environment. Graduates are also prepared to continue with further studies in Earth/Environmental sciences and engineering, business, public policy, international studies, law, and medicine. The EEE program is accredited as an environmental engineering program by the Engineering Accreditation Commission of ABET, http://www.abet.org. Practice and theory are both critical to the advancement of earth and environmental engineering; the department works actively with students to reach their learning outcomes and research and career goals.

Undergraduate Program Objectives
1. Graduates equipped with the necessary tools (mathematics, chemistry, physics, earth sciences, and engineering science) will understand and implement the underlying principles used in the engineering of processes and systems.
2. Graduates will be able to pursue careers in industry, government agencies, and other organizations concerned with the environment and the provision of primary and secondary materials and energy, as well as continue their education as graduate students in related disciplines.
3. Graduates will possess the basic skills needed for the practice of Earth and Environmental Engineering, including measurement and control of material flows through the environment; assessment of environmental impact of past, present, and future industrial activities; and analysis and design of processes for remediation, recycling, and disposal of used materials.
4. Graduates will practice their profession with excellent written and communication skills and with professional ethics and responsibilities.

Undergraduate Student Outcomes
1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on teams whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

The Curriculum
The first two years of the EEE program are similar to those of other engineering programs. Students are provided with a strong foundation in basic sciences and mathematics, as well as the liberal arts core. Specific to the EEE program is an early and sustained introduction to earth science and environmental engineering, and options for a number of science courses to meet the specific interests of each student. The junior and senior years of the program consist of a group
of required courses in engineering science and a broad selection of technical electives organized. The department website (eee.columbia.edu) details the required courses and other information.

Several Columbia departments, such as Civil Engineering, Mechanical Engineering, and Earth and Environmental Sciences (Lamont-Doherty Earth Observatory), as well as the Mailman School of Public Health, contribute courses to the EEE program. EEE students are strongly encouraged to work as summer interns in industry or agencies on projects related to Earth and Environmental Engineering.

**GRADUATE PROGRAMS**

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–E6004 and should consult their program for specific PDL requirements.

**M.S. in Earth and Environmental Engineering (M.S.-EEE)**

The M.S.-EEE program is designed for engineers and scientists who plan to pursue, or are already engaged in, environmental management/development careers. The focus of the program is the environmentally sound mining and processing of primary materials (minerals, energy, and water) to the recycling and proper disposal of used materials. The program also includes technologies for assessment and remediation of damages to the environment including water treatment, processing of mine tailings, and carbon capture, utilization and storage. Students can choose a pace that allows them to complete the M.S.-EEE requirements while being employed.

M.S.-EEE graduates are specially qualified to work for engineering, financial startup, and operating companies engaged in the earth resources development and environmental industries and technologies, environmental groups in all industries, and for city, state, and federal agencies responsible for the environment and energy/resource conservation. At the present time, the U.S. environmental industry comprises nearly 30,000 big and small businesses with total revenues of more than $150 billion. Sustainable development, climate change adaptation and mitigation, as well as environmental quality have become top priorities of government and industries in the United States and many other nations.

This M.S. program is offered in collaboration with the Departments of Civil Engineering and Earth and Environmental Sciences. Many of the teaching faculty are affiliated with Columbia’s Earth Engineering Center. For students with a B.S. in engineering, at least 30 points (ten courses) are required. Students may carry out a research project (3 credits) or write a thesis worth 6 points. A number of areas of study are available for the M.S.-EEE, and students may choose courses that match their interest and career plans.

Additionally, there are three optional concentrations in the program, in each of which there are a number of required specific core courses and electives. The concentrations are described briefly below; details and the lists of specific courses for each track are available from the department. Students interested in a specific focus in Mining Engineering or related fields should consult their faculty adviser for relevant course listings.

**Water Resources and Climate Risks**

Climate-induced risk is a significant component of decision making for the planning, design, and operation of water resource systems, and related sectors such as energy, health, agriculture, ecological resources, and natural hazards control. Climatic uncertainties can be broadly classified into two areas: (1) those related to anthropogenic climate change; (2) those related to seasonal- to century-scale natural variations. Climate change impacts the design of physical, social, and financial infrastructure systems to support the sectors listed above. The climate variability and predictability issues impact systems operation, and hence design. The goal of the M.S. concentration in water resources and climate risks is to provide (1) a capacity for understanding and quantifying the projections for climate change and variability in the context of decisions for water resources and related sectors of impact; and (2) skills for integrated risk assessment and management for operations and design, as well as for regional policy analysis and management. Required classes include:

- CEE E4250 Hydrosysms
- CEE E4163 Sustainable water treatment and reuse
- EAEE E4257 Environmental data analysis and modeling

**Sustainable Energy**

Building and shaping the energy infrastructure of the twenty-first century is one of the central tasks for modern engineering. The purpose of the sustainable energy concentration is to expose students to modern energy technologies and infrastructures and to the associated environmental, health, and resource limitations. Emphasis will be on energy generation and use technologies that aim to overcome the limits to growth that are experienced today. Energy and economic well-being are tightly coupled. Fossil fuel resources are still plentiful, but access to energy is limited by environmental and economic constraints. A future world population of 10 billion people trying to approach the standard of living of the developed nations cannot rely on today’s energy technologies and infrastructures without severe environmental impacts. Concerns over climate change and changes in ocean chemistry require reductions in carbon dioxide emissions, but most alternatives to conventional fossil fuels, including nuclear energy, are too expensive to fill the gap. Yet access to clean, cheap energy is critical for providing minimal resources: water, food, housing, and transportation.

Concentration-specific classes will sketch out the availability of resources, their geographic distribution, the economic and environmental cost of resource extraction, and avenues for increasing energy utilization efficiency, such as cogeneration, district heating, and distributed generation of energy. Classes will discuss technologies for efficiency improvement in the generation and consumption sector; energy recovery from solid wastes;...
alternatives to fossil fuels, including solar and wind energy, energy storage; and technologies for addressing the environmental concerns over the use of fossil fuels. Classes on climate change, air quality, and health impacts focus on the consequences of energy use. Policy and its interactions with environmental sciences and energy engineering will be another aspect of the concentration. Additional specialization may consider region-specific energy development. Required classes include:
• EAAE E4002 Alternative energy resources
• EEEL E4220 Energy system economics and optimization

Sustainable Mining and Materials
Earth mineral and metal resources are the backbone of civilization and are critical to economic development and meeting the demands of a growing population. Their development today faces several big challenges: (1) declining value content in the available ore bodies and poor quality of the resources; (2) increasing focus on safety and health risks, and environmental impacts; (3) inefficient and high energy and water consumption; (4) huge risks associated with waste generation and management.

It is well recognized in the earth resource development industry that the traditional processing paradigm is no longer sustainable and cannot address these serious challenges. The overall goal of industry to develop and implement technologies for sensible and sustainable use of earth resources is part of a “mines of the future” paradigm, which encompasses topics such as mine-to-metal integration, modular processing, digital optimization, machine learning and AI, sensors and chemometrics, benign process chemicals, and a host of other forward-looking concepts. A similar effort and outlook exists for urban mining and recycling. The transformation of waste to energy and the recovery of minerals from recycling streams are examples of these areas that EEE is a world leader in. The EEE program in Sustainable Mining and Materials integrates foundational engineering principles and processes with the transformational innovations under development in the earth resources management sector. Core classes include:
• EAAE E4160 Solid and hazardous waste management
• EAAE E4200 Introduction to sustainable production of earth mineral & metal resources
• EAAE E4228 Separation science and technology in sustainable earth resources development

M.S. in Carbon Management (MCM)
The program is designed to prepare students to create and implement multifaceted solutions to the carbon problem with an in-depth understanding of the complexity and multidisciplinary nature of the issues.

Coursework includes 30 credits of graduate coursework. Depending on student's background, some undergraduate level science courses may be required. Each student will develop an academic plan with the program director. There are three options for completing the 30 credits:
• 30 credits of lecture courses
• 24 credits of lecture courses and 6 credits of research with a culminating Master's Thesis
• 27 credits of lecture courses and 3 credits of research with a concluding report

Core courses:
• EAAE E4300/E6212 Introduction to carbon management
• EAAE E4302 Carbon capture
• EAAE E4301 Carbon storage
• EAAE E4305 CO2 utilization and conversion

Professional Degree; Engineer of Mines
The program is designed for engineers who wish to do advanced work beyond the level of the M.S. degree but who do not desire to emphasize research. Admissions requirements include Undergraduate engineering degree, minimum 3.0 GPA, and GRE.

Candidates must complete at least 30 credits of graduate work beyond the M.S., or 60 points of graduate work beyond the B.S. No thesis is required. All degree requirements must be completed within 5 years of the beginning of the first course credited toward the degree.

Coursework includes four core required courses and six elective courses from a pre-approved list of choices.

Core courses:
• EAAE E4001 Industrial ecology of earth resources
• EAAE E4009 Geographic information systems (GIS) for resource, environmental and infrastructure management

Elective courses must be six courses at the 4000 or higher level from within the Earth and Environmental Engineering Department, the Chemical Engineering Department, or others as approved by the adviser. These include but are not limited to: EAAE E4900, CHEE E4252, CIEE E4252, EAAE E4257, ELEN E4004, EAAE E4160, EAAE E4300, EAAE E6132, EAAE E6140, EAAE E6150, EAAE E6212. Although not required, interested students may choose to complete up to six credits in EAAE E9309.

Doctoral Programs
EE offers two doctoral degrees: (1) the Eng.Sc.D. degree, administered by Columbia Engineering; and (2) the Ph.D. degree, administered by the Graduate School of Arts and Sciences.

Doctoral Qualifying Examination and Research Proposal
Before the end of the first semester in the doctoral program, the student and their adviser will set up an advisory committee of two or three faculty members. This committee will meet at least once a semester to assess academic and research progress of the student and to recommend corrective action in case of emerging or existing deficiencies.

Doctoral students are required to pass a qualifying exam within their first year into the program. They will submit and defend their research proposal approximately one year after successful completion of the qualifying exam. Submission of the dissertation and thesis defense will follow general University rules.

The qualifying examination will be an oral exam administered by three faculty members. The adviser of the student will be a member of the exam
committee but may not be the chair. The students will be examined in their understanding of fundamentals as they apply in the areas of research of the department: water resources, materials processing, energy, and chemical and biochemical processes. It is expected that each question period will last about 20 minutes, of which 15 minutes will be led by the faculty member from the area and the remaining 5 minutes will be open for questions by all faculty present at the exam. There will be a final period of 20 minutes for general questions.

All graduate students are expected to have a background equivalent to the required core of our undergraduate program. They have, of course, an opportunity to make up for any deficiency in their master’s program. In order to be prepared for the exam, students can take at least one course in each core area during their first two semesters at Columbia (see website for up-to-date course listing). In case the student declares an explicit minor for up-to-date course listing). In case the student declares an explicit minor in another department, the qualifying exam requirements will be modified in consultation with the graduate committee. The minor has to be approved by both departments.

The engineering objectives of EEE research and education include:

- **Provision and disposal of materials:** environmentally sustainable extraction and processing of primary materials; manufacturing of derivative products; recycling of used materials; management of industrial residues and used products; materials-related application of industrial ecology.

- **Management of water resources:** understanding, prediction, and management of the processes that govern the quantity and quality of water resources, including the role of climate; development/operation of water resource facilities; management of water-related hazards.

- **Energy resources and carbon management:** mitigation of environmental impacts of energy production; energy recovery from waste materials; advancement of energy efficient systems; new energy sources; development of carbon sequestration strategies.

- **Sensing and remediation:** understanding of transport processes at different scales and in different media; containment systems; modeling flow and transport in surface and subsurface systems; soil/water decontamination and bioremediation.

### COURSES IN EARTH AND ENVIRONMENTAL ENGINEERING

**EAE E2002x Alternative energy resources**

3 pts. Lect: 3. Professor Steinhardt. Unconventional, alternative energy resources. Technological options and their role in the world energy markets. Comparison of conventional and unconventional, renewable and nonrenewable energy resources and analysis of the consequences of various technological choices and constraints. Economic considerations, energy availability, and the environmental consequences of large-scale, widespread use of each particular technology. Introduction to carbon dioxide capture and carbon dioxide disposal as a means of sustaining the fossil fuel option.

**EAE E2100x A better planet by design**


**CHEE E3010x Principles of chemical engineering thermodynamics**

3 pts. Lect: 3. Professor Simunovic. Prerequisite(s): CHEM UN1403 or equivalent. Teaches the formal relationships in the physical world, connecting the fundamental principles with the basis of chemical engineering practice. Topics include the first and second laws of thermodynamics, concepts such as energy and entropy, the equations that relate heat to other forms of energy, properties of ideal and real gases, fluids, single and multicomponent systems, phase and chemical equilibria, and the practical implications of these phenomena to systems from the molecular scale to the living world.

**EAE E3101y Earth resource production systems**

3 pts. Lect: 3. Not offered in 2022–2023. Technologies and equipment common to a wide range of surface and subsurface engineering activities: mine reclamation, hazardous waste remediation, discovering and operating surface and underground mines, detection and removal of hidden underground objects, waste disposal, dredging and harbor rehabilitation, and tunneling for transportation or water distribution systems. These methods and equipment are examined as they apply across the spectrum from mining to environmental engineering projects. The aim is to provide a broad background for earth and environmental engineers in careers involving minerals and industrial, large-scale environmental projects.

**EAE E3103x Energy, minerals, and materials systems**

3 pts. Lect: 3. Professor Farinato. Prerequisite(s): MSAE E3111 or MECE E3301 and ENME E3161 or MECE E3100 or equivalent Corequisite(s): MSAE E3111 or MECE E3301 and ENME E3161 or MECE E3100 or equivalent. Overview of energy resources, resource management from extraction and processing to recycling and final disposal of wastes. Resources availability and resource processing in the context of the global natural and anthropogenic material cycles; thermodynamic and chemical conditions including nonequilibrium effects that shape the resource base; extractive technologies and their impact on the environment and the biogeochemical cycles; chemical extraction from mineral ores, and metallurgical processes for extraction of metals. In analogy to metallurgical processing, power generation and the refining of fuels are treated as extraction and refining processes. Large scale of power generation and a discussion of its impact on the global biogeochemical cycles.

**MSAE E3141y Processing of metals and semiconductors**

3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): MSAE E3103 or equivalent. Synthesis and production of metals and semiconductors with engineered microstructures for desired properties. Includes high-temperature, aqueous, and electrochemical processing; thermal and mechanical processing of metals and alloys; casting and solidification; diffusion, microstructural evolution, and phase transformations; modification and processing of surfaces and interfaces; deposition and removal of thin films. Processing of Si and other materials for elemental and compound semiconductor-based electronic, magnetic, and optical devices.

**EAE E3185y Summer fieldwork for earth and environmental engineers**

0.5 pt. Not offered in 2022–2023. Undergraduates in earth and environmental engineering may spend up to three weeks in the field under staff direction. The course consists of mine, landfill, plant, and major excavation site visits and brief instruction of surveying methods. A final report is required.

**EAE E3200x Applied transport and chemical rate phenomena**

EAEE E3221x Environmental geophysics
Introduction to applied and environmental geophysics methods. Overview of principles of geophysics, geophysical methods and techniques (seismic, ground penetrating radar, resistivity, frequency em, and magnetics), and theory and practical aspects of data processing and inversion. Examination of geophysical case studies for engineering and environmental purposes.

CIEE E3250y Hydrosystems engineering
3 pts. Lect: 3. Professor Kelly.
Prerequisite(s): CHEN E3110 or ENME E3161 or equivalent, or instructor’s permission. A quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulic in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for non-point source pollution. Spatial hydrologic analysis using GIS and watershed models.

CIEE E3255y Environmental control and pollution reduction systems
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): EAEE E3200 or ENME E3161 or MECE E3100. Sources of solid/gaseous air pollution and the technologies used for modern methods of abatement. Air pollution and its abatement from combustion of coal, oil, and natural gas and the thermodynamics of heat engines in power generation. Catalytic emission control is contrasted to thermal processes for abating carbon monoxide, hydrocarbons, oxides of nitrogen and sulfur from vehicles and stationary sources. Processing of petroleum for generating fuels. Technological challenges of controlling greenhouse gas emissions. Biomass and the hydrogen economy coupled with fuel cells as future sources of energy.

EAEE E3800y Earth and environmental engineering laboratory, I
Prerequisite(s): CHEE E3010. Corequisite(s): CIEE E3255. Experiments on fundamental aspects of earth and environmental engineering with emphasis on the applications of chemistry, biology and thermodynamics to environmental processes: energy generation, analysis and purification of water, environmental biology, and biochemical treatment of wastes. Students will learn the laboratory procedures and use analytical equipment firsthand, hence demonstrating experimentally the theoretical concepts learned in class.

EAEE E3900x and y–S3900 Undergraduate research in earth and environmental engineering
0–3 pts. Directed study. Members of the faculty. This course may be repeated for credit, but no more than 3 points of this course may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in Earth and Environmental Engineering, or carry out a special project under the supervision of EAEE faculty. Credit for the course is contingent on the submission of an acceptable thesis or final report. This course cannot substitute for the Undergraduate design project (EAEE E3999 or EAE E3999).

EAEE E3990y Environmental microbiology
3 pts. Lect: 3. Professor Chandran.
Prerequisite(s): CHEM UN1404 or equivalent. Fundamentals of microbiology, genetics and molecular biology, principles of microbial nutrition, energetics and kinetics, application of novel and state-of-the-art techniques in monitoring the structure and function of microbial communities in the environment, engineered processes for biochemical waste treatment and bioremediation, microorganisms and public health, global microbial elemental cycles.

EAEE E3995x, y, and z Fieldwork
1 pt. Members of the faculty.
Prerequisite(s): Instructor’s permission. Obtained internship and approval from faculty advisor. Written application must be made prior to registration outlining proposed internship and study program. Final reports required. May not be taken for pass/fail credit or audited. Fieldwork credits may not count toward any major core, technical elective, and nontechnical requirements.

EAEE E4000x Machine learning for environmental engineering and science
3 pts. Lect: 2.5. Professor Gentine.
Prerequisite(s): Computer language (Python or Julia), some linear algebra and machine learning. Aimed at understanding and testing state-of-the-art methods in machine learning applied to environmental sciences and engineering problems. Potential applications include but are not limited to remote sensing, and environmental and geophysical fluid dynamics. Includes testing “vanilla” ML algorithms, feedforward neural networks, random forests, shallow vs deep networks, and the details of machine learning techniques.

EAEE E4001x Industrial ecology of earth resources
3 pts. Lect. 3. Professor Bourtsalas.
Industrial ecology examines how to reconfigure industrial activities so as to minimize the adverse environmental and material resource effects on the planet. Engineering applications of methodology of industrial ecology in the analysis of current processes and products and the selection and design of environmentally superior alternatives. Home assignments of illustrative quantitative problems.

EAEE E4003x Aquatic chemistry
3 pts. Lect. 3. Professor Yip.
Prerequisite(s): CHEE E3010. Principles of physical chemistry applied to equilibria and kinetics of aqueous solutions in contact with minerals and anthropogenic residues. The scientific background for addressing problems of aqueous pollution, water treatment, and sustainable production of materials with minimum environmental impact. Hydrolysis, oxidation-reduction, complex formation, dissolution and precipitation, predominance diagrams; examples of natural water systems, processes for water treatment and for the production of inorganic materials from minerals.

EAEE E4004x Physical processing and recovery of solids
Generalized treatment of processes for solids separation. Applications to materials processing and handling; mining; solid waste, recycling, and resource recovery; construction materials and debris; scrap materials, yard and park wastes. Economic considerations and context. Relevant materials properties and bulk materials analyses. Process system flow-sheets and analysis. Solid/solid, solid/liquid, and solid/gas separation process. Liberation, concentration, and auxiliary processes. Design of separation machines: types and intensities of force involved; scaling-up factors. Laboratory demonstrations and a field trip will be included.

EAEE E4005x Near-surface engineering geophysics
Geophysical methods as applicable to engineering problems. Principles of geophysics and noninvasive imaging techniques (inverse technology) and benefits and pitfalls of geophysics vs. direct imaging methods. Discussion of theory of each method. Discussion of data acquisition, processing and interpretation for each method. Treatment of several case studies. Class-wide planning and execution of small-scale geophysical survey.
EAEE E4007y Environmental geophysics field studies
3 pts. Lect: 3. Not offered in 2022–2023. Application of geophysical methods to noninvasive assessment of the near surface. First part consists of series of two-hour lectures of physics and math involved in instrumental methods and data acquisition and processing. The field (nine field days) students plan surveys; collect and analyze geophysical data in teams; learn how to integrate geophysical data with invasive data, hydrological, geological, engineering, and contaminant transport models; and develop a comprehensive and justifiable model of the subsurface. Geophysical methods include GPR (Ground Penetrating Radar), conductivity, and magnetic and seismic methods. Field applications include infrastructure/ environmental assessment, archeological studies, and high resolution geology.

EAEE E4009x Geographic information systems (GIS) for resource, environmental and infrastructure management
3 pts. Lect: 3. Professor Gorokhovich. Prerequisite(s): Instructor’s permission. Basic concepts of spatial data representation and organization, and analytical tools are introduced and applied in a form of case studies from hydrology, environmental conservation, and emergency response to natural or man-made hazards, among others. Technical content includes geographic topics (map projections, cartography, etc.), spatial statistics, database design and use, interpolation and visualization of spatial surfaces and volumes, and multicriteria decision analysis. Students will learn the basics of ArcGIS Pro, Model Builder, and Python. Elective term projects or final exams emphasize spatial information synthesis toward the solution of a specific problem.

EAEE E4010y Remote sensing and environmental change
3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): EAEE E4009 or EESC GU4050 or instructor’s permission. Practical and theoretical foundations for the application of remote sensing techniques to identification and monitoring of environmental change. Designing and applying spectral indices for assessment and monitoring, time series analysis of remote sensing data for analyzing environmental problems. Discussions of published literature relevant to the central topic covered in class. Analysis of remote sensing data using IRI data library.

EAEE E4011y Industrial ecology for manufacturing
3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): EAEE E4001 or instructor’s permission. Application of industrial ecology to Design for Environment (DFE) of processes and products using environmental indices of resources consumption and pollution loads. Introduction of methodology for Life Cycle Assessment (LCA) of manufactured products. Analysis of several DFE and LCA case studies. Term project required on use of DFE/LCA on a specific product/process: (a) product design complete with materials and process selection, energy consumption, and waste loadings; (b) LCA of an existing industrial or consumer product using a commercially established method.

CHEE E4050x Industrial and environmental electrochemistry

EAEE E4100x Better planet by design
3 pts. Lect: 3. Professor Bourtsalas. Foundational for the Master of Science in Earth and Environmental Engineering degree. Provides broader understanding of engineering tools critical/essential to success in large-scale, engineering projects. Divided into two parts: Module on global/regional flows, and systems approach, and Module on Engineering Principles in Earth & Environmental Engineering. Guest lectures on several topics will be provided.

ECIA W4100y Management and development of water systems
3 pts. Lect: 3. Not offered in 2022–2023. Decision analytic framework for operating, managing, and planning water systems, considering changing climate, values and needs. Public and private sector models explored through U.S.-international case studies on topics ranging from integrated watershed management to the analysis of specific projects for flood mitigation, water and wastewater treatment, or distribution system evaluation and improvement.

CIEE E4116x Energy harvesting
3 pts. Lect: 3. Professor Yin. Prerequisite(s): ENME E3114 or equivalent, or instructor’s permission. Criterion of energy harvesting, identification of energy sources. Theory of vibrations of discrete and continuous system, measurement and analysis. Selection of materials for energy conversion, piezoelectric, electromagnetic, thermoelectric, photovoltaic, etc. Design and characterization, modeling and fabrication of vibration, motion, wind, wave, thermal gradient, and light energy harvesters; resonance phenomenon, power electronics and energy storage and management. Applications to buildings, geothermal systems, and transportation.

CHEE E4140x Engineering separations processes
3 pts. Lect: 3. Professor Durning. Prerequisite(s): CHEM E3100, E3120, and E3210 or instructor’s permission. Design and analysis of unit operations employed in chemical engineering separations. Fundamental aspects of single and multistaged operations using both equilibrium and rate-based methods. Examples include distillation, absorption and stripping, extraction, membranes, crystallization, bioseparations, and environmental applications.

EAEE E4150y Air pollution prevention and control
3 pts. Lect: 3. Professor Rhenakis. Adverse effects of air pollution, sources and transport media, monitoring and modeling of air quality, collection and treatment techniques, pollution prevention through waste minimalization and clean technologies, laws, regulations, standards, and guidelines.

EAEE E4160y Solid and hazardous waste management

CIEE E4163y Sustainable water treatment and reuse
3 pts. Lect: 3. Professor Knowles. Prerequisite(s): CHEM UN1403-1404 or equivalent, MECE E3301 or equivalent, PHYS UN1402 or equivalent. Corequisite(s): CHEM E4201, EAAE E3103. Survey course on electrochemical energy storage with a focus on closed-form cells. Fundamentals of thermodynamics will be reviewed and fundamentals of electrochemistry introduced. Application of fundamentals to devices such as batteries, flow batteries, and fuel cells. Device optimization with respect to energy density, power density, cycle life, and capital cost will be considered.

EAEE E4180y Electrochemical energy storage systems
3 pts. Lect: 3. Professor Steingart. Prerequisite(s): CHEM UN1403-1404 or equivalent, MECE E3301 or equivalent, PHYS UN1402 or equivalent. Corequisite(s): CHEM E4201, EAAE E3103. Survey course on electrochemical energy storage with a focus on closed-form cells. Fundamentals of thermodynamics will be reviewed and fundamentals of electrochemistry introduced. Application of fundamentals to devices such as batteries, flow batteries, and fuel cells. Device optimization with respect to energy density, power density, cycle life, and capital cost will be considered.

EAEE E4190x Photovoltaic systems engineering and sustainability
3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): Senior standing or instructor’s permission. A systems approach for intermittent renewable energy involving the study of resources, generation, demand, storage, transmission, economics and politics. Study of current and emerging photovoltaic technologies, with focus on basic sustainability metrics (e.g., cost, resource availability, and life-cycle environmental impacts). The status and potential of first- and second-generation photovoltaic technologies (e.g., crystalline and amorphous Si, CdTe, CIGS) and emerging third-generation ones. Storage options to overcome the intermittency constraint. Large scales of renewable energy technologies and plug-in hybrid electric cars.
EAEE E4200y Introduction to sustainable production of earth mineral & metal resources
3 pts. Lect: 3. Professors Nagaraj.
Prerequisite(s): EAEE E3103 and undergraduate level courses in chemistry (especially inorganic, physical and organic). Introductory course focused on engineering principles and unit operations involved in sustainable processing of primary and secondary earth mineral and metal resources. Covers entire value chain, viz., aspects of economic resource deposits, mining, fundamental principles and processes for size reduction, separations based on physical and chemical properties of minerals and metals, solid-liquid separation, waste and pollution management, water and energy efficiency and management, safety and health, environmental impact assessment and control, and economic efficiency. Special emphasis on concepts and practical applications within "mines of the future" framework to highlight innovations and transformational technological changes in progress.

EAIA W4200y Alternative energy resources
3 pts. Lect: 3. Professor Steingart.
Unconventional, alternative energy resources. Technological options and their role in the world energy markets. Comparison of conventional and unconventional, renewable and nonrenewable, energy resources and analysis of the consequences of various technological choices and constraints. Economic considerations, energy availability, and the environmental consequences of large-scale, widespread use of each particular technology. Introduction to carbon dioxide disposal as a means of sustaining the fossil fuel option. Recitation section required.

EAEE E4210x Thermal treatment of waste and biomass materials
Prerequisite(s): CHEE E3010 or the equivalent or instructor’s permission. Origins, quantities generated, and characterization of solid wastes. Chemical and physical phenomena in the combustion or gasification of wastes. Application of thermal conversion technologies, ranging from combustion to gasification and pyrolysis. Quantitative description of the dominant waste to energy processes used worldwide, including feedstock preparation, moving grate and fluid bed combustion, heat transfer from combustion gases to steam, mitigation of high-temperature corrosion, electricity generation, district heating, metal recovery, emission control, and beneficial use of ash residues.

EEEL E4220x Energy system economics and optimization
3 pts. Lect: 3. Professor Xu.
Prerequisite(s): Basic linear algebra, basic probability and statistics, and basic programming skills. Fundamental of power system economics over which the current electricity markets are designed. Formulation of unit commitment and economic dispatch as mathematical optimization. Modeling of thermal generators, renewable generators, energy storage, and other grid resources in power system optimization. Introduction of equilibriums in electricity markets. Introduction of ancillary service markets. Overview of current energy system research topics. Designed for masters and doctoral students, but is also open to undergraduates with the appropriate foundation classes.

EAEE E4222y Interfacial engineering for sustainable energy and materials
3 pts. Lect: 3. Professor Farinato.
Prerequisite(s): EAEE E3103 or equivalent or instructor’s permission. Cross-disciplinary interfacial engineering principles and applications in sustainable energy and material science. Surface science and systems analysis across different technology sectors—material production and processing, waste management, device manufacture, composites, coatings, ceramics, membranes, biomaterials, and microelectronics.

EAEE E4228y Separation science and technology in sustainable earth resources development
3 pts. Lect: 3. Professors Nagaraj.
Prerequisite(s): EAEE E3103 and undergraduate level courses in chemistry (especially inorganic, physical and organic). Recommended: EAEE E4252, EAEE E4003, and EAEE E4200. Detailed study of the chemical and physicochemical principles underlying separations in development of earth resources in a safe and sustainable manner. Covers wide-range of solid-solid, solid-liquid and liquid-liquid separations used in processing of mineral resources. Interfacial science and engineering principles of important industrial processes of flotation, flocculation, dewatering, interfacial transport, magnetic/ gravity/electrostatic separations, solvent extraction, solid-support extraction, crystallization and precipitation. Emphasis on concepts in interfacial chemistry and concepts associated with ‘mines of the future’ framework.

EAEE E4241x Solids handling and transport systems
Analysis and design of transportation systems for bulk solids in tunnels, mines, and large excavations. Design of hoisting, cable transport, rail and trackless haulage systems, conveyor belts, selection of loaders, excavators, off-highway trucks, and draglines for large excavations.

CIEE E4250x or y Hydrosystems
3 pts. Lect: 3. Professor Gentine.
Prerequisite(s): CHEN E3101 or ENME E3161 or equivalent, or the instructor’s permission. The hydrologic cycle and relevant atmospheric processes; water and energy balance; radiation; boundary layer; precipitation formation; evaporation; vegetation transpiration; infiltration; storm runoff; snowmelt; and flood processes. Routing of runoff and floodwaters. Groundwater flow and the hydraulics of wells. Probabilistic modeling, and extreme-value theory.

CHEE E4252x Introduction to surface and colloid chemistry
Prerequisite(s): Elemental physical chemistry. The principles of surfaces and colloid chemistry critical to range of technologies indispensable to modern life. Surface and colloid chemistry has significance to life sciences, pharmaceuticals, agriculture, environmental remediation and waste management, earth resources recovery, electronics, advanced materials, enhanced oil recovery, and emerging extraterrestrial mining. Topics include: thermodynamics of surfaces, properties of surfactant solutions and surface films, electrokinetic phenomena at interfaces, principles of adsorption and mass transfer and modern experimental techniques. Leads to deeper understanding of interfacial engineering, particulate dispersions, emulsions, foams, aerolsols, polymers in solution, and soft matter topics.

CIEE E4252y Foundations of environmental engineering
3 pts. Lect: 3. Professor Chandran.
Prerequisite(s): CHEM UN4031, or equivalent; ENME E3161 or equivalent. Engineering aspects of problems involving human interaction with the natural environment. Review of fundamental principles that underlie the discipline of environmental engineering, i.e., constituent transport and transformation processes in environmental media such as water, air, and ecosystems. Engineering applications for addressing environmental problems such as water quality and treatment, air pollution emissions, and hazardous waste remediation. Presented in the context of current issues facing the practicing engineers and government agencies, including legal and regulatory framework, environmental impact assessments, and natural resource management.

EAEE E4255x River and coastal hydraulics
Prerequisite(s): CHEN E3101 or ENME E3161 or the equivalent. Dynamics of flow and waves in rivers and coastal settings, with applications to flooding and mixing of saline and fresh waters, sediment transport. Integrative hydraulics modeling experience using numerical and analytical tools applied to complex real world setting, including concerns of anthropogenic change in rivers and estuaries and sea level fluctuations at the river-estuary boundary.

CIEE E4257y Groundwater contaminant transport and remediation
EAEE E4257y Environmental data analysis and modeling
3 pts. Lect: 3. Professor Xu.
Prerequisite(s): IOR E365B, E4150, or STAT GU4001 or equivalent; some exposure to linear algebra; basic programming experiences. Introduction parametric and nonparametric statistical models applied to climate and environmental data analysis. Time and space data analysis methods will be focused, including clustering, autoregressive models, trend analysis, Bayesian analysis, missing data imputation, geostatistics, and principal components analysis. Application to problems of climate variation and change; hydrology; air, water and soil pollution dynamics; disease propagation; ecological change; and resource assessment. The class requires the use of R with hands-on programmes and a term project applied to a current environmental data analysis problem.

EAEE E4262y Space exploration and mining
Needs and opportunities for space exploration and mining, resources in planets and asteroids, history of human colonization, terraforming Mars, Titan, and the moon, safety and health issues, benign mining, space junk extraction, microbial mining.

EAEE E4300x or y Introduction to carbon management
3 pts. Lect: 3. Professor Park.
Prerequisite(s): Undergraduate level mathematics and science, or instructor’s permission. Introduction to natural and anthropogenic carbon cycle, and carbon and climate. Rationale and need to manage carbon and tools with which to do so (basic science, psychology, economics and policy background, negotiations and society; emphasis on interdisciplinary and inter-dependent approach). Simple carbon emission model to estimate the impacts of a specific intervention with regard to national, per capita, and global emissions. Student-led case studies (e.g., reforestation, biofuels, CCS, efficiency, alternative energy) to illustrate necessary systems approach required to tackle global challenges.

EAEE E4301y Carbon storage
3 pts. Lect: 3. Professor Kelly and Kelemen.
Prerequisite(s): Undergraduate level mathematics and science, or instructor’s permission. Major technologies to capture carbon dioxide via new or retrofitted power plant designs, during industrial processes, and from ambient air. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE E4302x or y Carbon capture
3 pts. Lect: 3. Professor Bourtsalas.
Prerequisite(s): Undergraduate level math and science or instructor’s permission. Major technologies to store carbon dioxide, geological, ocean, and in the carbon chemical pool. Carbon dioxide transport technologies also covered. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE E4303x or y Carbon measurement and monitoring
Prerequisite(s): Undergraduate level math and science or instructor permission. Sources of various GHGs (whether fossil industrial or biogenic), their chemical behavior, interactions, and global warming potential once airborne; available measurement, monitoring, and detection technologies to track gas emissions, including leakage from storage sites. Carbon accounting and reporting methodologies such as life cycle analysis, and corporate carbon footprinting. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE E4304x Closing the carbon cycle
3 pts. Lect: 3. Professor Eisenberger.
Prerequisite(s): Calculus, basic inorganic chemistry, and basic physics, including thermodynamics, or instructor’s permission. Introduction to complex systems, their impact on our understanding and predictability of the carbon cycle, the use of systems analysis and modeling tools, as well as Bayesian statistics and decision theory for evaluating various solutions to close the carbon cycle, a detailed examination of the geochemical carbon cycle, major conceptual models that couple its changes to climate change, analysis of the anthropogenic carbon sources and sinks and role of carbon in energy production, closing the carbon cycle impacts on energy security, economic development and climate change protection, analysis of solutions to close the carbon cycle.

EAEE E4305y Carbon utilization and conversion
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): Undergraduate level thermodynamics or instructor’s permission. Introduction to various CO2 utilization and conversion technologies that can reduce the overall carbon footprint of commodity chemicals and materials. Fundamentals of thermodynamics, fluid mechanics, reaction kinetics, catalysis and reactor design will be discussed using technological examples such as enhanced oil recovery, shale fracking, photo and electrochemical conversion of CO2 to chemical and fuels, and formation of solid carbonates and their various uses. Life cycle analyses of potential products and utilization schemes will also be discussed, as well as the use of renewable energy for CO2 conversion.

EAEE E4350x Planning and management of urban hydrologic systems
3 pts. Lect: 3. Professor Rosenberg.
Prerequisite(s): ENME E3161 or equivalent. Introduction to runoff and drainage systems in an urban setting, including hydrologic and hydraulic analyses, flow and water quality monitoring, common regulatory issues, and mathematical modeling. Applications to problems of climate variation, land use changes, infrastructure operation and receiving water quality, developed using statistical packages, public-domain models, and Geographical Information Systems (GIS). Team projects that can lead to publication quality analyses in relevant fields of interest. Emphasis on the unique technical, regulatory, fiscal, policy, and other interdisciplinary issues that pose a challenge to effective planning and management of urban hydrologic systems.

EAEE E4361y Economics of earth resource industries
Prerequisite(s): EEA E3103 or instructor’s permission. Definition of terms. Survey of earth resource industries: resources, reserves, production, global trade, consumption of mineral commodities and fuels. Economics of recycling and substitution. Methods of project evaluation: estimation of operating costs and capital requirements, project feasibility, risk assessment, and environmental compliance. Cost estimation for reclamation/remediation projects. Financing of reclamation costs at abandoned mine sites and waste-disposal postclosure liability.

CHEE E4530y Corrosion of metals
Prerequisite(s): CHEN E3010 or equivalent. The theory of electrochemical corrosion, corrosion tendency, rates, and passivity. Application to various environments. Cathodic protection and coatings. Corrosion testing.

EAEE E4550x Catalysis for emissions control
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): One year of general college chemistry. Fundamentals of heterogeneous catalysis including modern catalytic preparation techniques. Analysis and design of catalytic emissions control systems. Introduction to current industrial catalytic solutions for controlling gaseous emissions. Introduction to future catalytically enabled control technologies.

EAEE E4560y Particle technology
Prerequisite(s): ENME E3161 and MSAE E3111 or equivalent. Introduction to engineering processes involving particulates and powders. The fundamentals of particle characterization, multiphase flow behavior, particle formation, processing and utilization of particles in various engineering applications with examples in energy and environment related technologies. Engineering of functionalized particles and design of multiphase reactors and processing units with
emphasis on fluidization technology. Particle technology is an interdisciplinary field. Due to the complexity of particulate systems, particle technology is often treated as art rather than science. In this course, the fundamental principles governing the key aspects of particle science and technology are introduced along with various industrial examples.

EAAE E4901y Environmental microbiology
3 pts. Lect: 3. Professor Chandran.
Basic microbiological principles; microbial metabolism; identification and interactions of microbial populations responsible for the biotransformation of pollutants; mathematical modeling of microbiologically mediated processes; biotechnology and engineering applications using microbial systems for pollution control.

EAAE E4950x Environmental biochemical processes
3 pts. Lect: 3. Professor Chandran. Offered only in odd years.
Prerequisite(s): EAAE E4901, E4003, CIEE E4252, or instructor’s approval. Qualitative and quantitative considerations in engineered environmental biochemical processes. Characterization of multiple microbial reactions in a community and techniques for determining associated kinetic and stoichiometric parameters. Engineering design of several bioreactor configurations employed for biochemical waste treatment. Mathematical modeling of engineered biological reactors using state-of-the-art simulation packages.

EAAE E4999x and y Fieldwork
1 pt. Members of faculty.
Prerequisite(s): Instructor’s written permission. Only EAAE graduate students who need relevant off-campus work experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed study program. Final reports required. This course may not be taken for pass/fail credit or audited. International students must also consult with the International Students and Scholars Office.

EAAE E6132y Numerical methods in geomechanics
Prerequisite(s): EAAE E3112 and CIIE E4241 or instructor’s permission. A detailed survey of numerical methods used in geomechanics, emphasizing the Finite Element Method (FEM). Review of the behavior of geological materials. Water and heat flow problems. FEM techniques for solving nonlinear problems, and simulating incremental excavation and loading on the surface and underground.

EAAE E6140y Environmental physicochemical processes
3 pts. Lect: 3. Professor Yip.
Prerequisite(s): CIEE E4252 and CIEE E4163 or the equivalent, or the instructor’s permission. Fundamentals and applications of key physicochemical processes relevant to water quality engineering (such as water treatment, waste water treatment/reuse/recycling, desalination) and the natural environment (e.g., lakes, rivers, groundwater).

EAAE E6150y Industrial catalysis
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): EAAE E4550 or equivalent, or instructor’s permission. Fundamental principles of kinetics, characterization and preparation of catalysts for production of petroleum products for conventional transportation fuels, specialty chemicals, polymers, food products, hydrogen and fuel cells and the application of catalysis in biomass conversion to fuel. Update of the ever changing demands and challenges in environmental applications, focusing on advanced catalytic applications as described in modern literature and patents.

EAAE E6151y Applied geophysics

EAAE E6181x Advanced electrochemical energy storage
3 pts. Lect: 3. Professor Steingart.
Prerequisite(s): EAAE E4180, EAAE E4002. Most modern commercial implementations of electrochemical energy storage are not fully deterministic: provides context and best-hypotheses for modern challenges. Topics include: current understanding of lithium/lithium anode solid-electrolyte-interphase, reversible and irreversible side reactions in redox flow systems, electrochemically correlated mechanical fracture at multiple scales, relationships between electrolyte solvation and electrode insertion, roughening, smoothing, and detachment behavior of metal anodes, best practices in structural, chemical, and microscopic characterization, morphological vs. macro-homogenous transport models, particle to electrode to cell non-linearity.

EAAE E6185y or y Complexity science
Prerequisite(s): Graduate standing and instructor’s permission. Survey of techniques, applications, and implications of complexity science and complex systems. Topics include systems dynamics, chaos, scaling, fat-tailed distributions, fractals, information theory, emergence, criticality, agent-based models, graph theory, and social networks. Applications will cover climate science, ecology, conflict, hydrology, geomorphology, physics, social theory, epidemiology, and governance.

EAAE E6210x or y Water, sanitation, and human health
Prerequisite(s): Instructor’s permission. In-depth analysis of issues relating to water, sanitation, and hygiene in both the developed and developing worlds. Hydrologic cycle, major causes of enteric morbidity and mortality, and design, financing and implementation of sanitation systems. For both engineering and public health students; intended to foster dialog between the two communities.

EAAE E6255x-E6256y Methods and applications of analytical decision making in mineral industries
Prerequisite(s): Instructor’s permission. Advanced study of decision-making problems with critical survey and applications of quantitative decision-making techniques in mineral industries. Systematic development of methods of the formulation, analysis, and resolution of these problems.

EAAE E6529x or y Water, sanitation, and human health
Prerequisite(s): Instructor’s permission. In-depth analysis of issues relating to water, sanitation, and hygiene in both the developed and developing worlds. Hydrologic cycle, major causes of enteric morbidity and mortality, and design, financing and implementation of sanitation systems. For both engineering and public health students; intended to foster dialog between the two communities.

EAAE E6220x Equilibria and kinetics in hydrometallurgical systems
Prerequisite(s): CHEE E4050 or EAAE E4003. Detailed examination of chemical equilibria in hydrometallurgical systems. Kinetics and mechanisms of homogeneous and heterogeneous reactions in aqueous solutions.

EAAE E6228y Theory of flotation
Prerequisite(s): CHEE E4252 or instructor’s permission. A detailed study of the physicochemical principles of the flotation process.

EAAE E6252y Advanced surface and colloid chemistry
Prerequisite(s): CHEE E4252. Applications of surface chemistry principles to wetting, flocculation, flotation, separation techniques, catalysis, mass transfer, emulsions, foams, aerosols, membranes, biological surfactant systems, microbial surfaces, enhanced oil recovery, and pollution problems. Appropriate individual experiments and projects. Lab required.

EAAE E6255x-E6256y Methods and applications of analytical decision making in mineral industries
Prerequisite(s): Instructor’s permission. Advanced study of decision-making problems with critical survey and applications of quantitative decision-making techniques in mineral industries. Systematic development of methods of the formulation, analysis, and resolution of these problems.
processing techniques, particularly mechanisms of adsorption, interactions of particles in solution, thinning of liquid films, and optimization techniques.

**EAEE E8231y Selected topics in hydro- and electrometallurgy**
3 pts. Lect: 3. Instructor to be announced. Prerequisite(s): EAEE E4003 and CHEE E4050, or instructor’s permission. Review of current research and literature in the field of hydrometallurgy, electrometallurgy, and corrosion. Topics will be selected by the instructor to illustrate the application of thermodynamics and rate phenomena to the design and control of electrochemical engineering processes.

**EAEE E8233x and y Research topics in particle processing**
0 pts. Professor Somasundaran. Emergent findings in the interactions of particles with reagents and solutions, especially inorganics, surfactants, and polymers in solution, and their role in grinding, flotation, agglomeration, filtration, enhanced oil recovery, and other mineral processing operations.

**EAEE E8273x-E8274y Mining engineering reports**

**EAEE E9271x and y–S9271 Earth and environmental engineering thesis**
0–6 pts. Members of the faculty. Research work culminating in a creditable dissertation on a problem of a fundamental nature selected in conference between student and adviser. Wide latitude is permitted in choice of a subject, but independent work of distinctly graduate character is required in its handling.

**EAEE E9273x-E9274y Earth and environmental engineering reports**
0–4 pts. May substitute for the formal master’s thesis, EAEE E9271, upon recommendation of the department.

**EAEE E9280x and y Earth and environmental engineering colloquium**
0 pts. Lect: 1.5. Professor Xu. All graduate students are required to attend the departmental colloquium as long as they are in residence. Advanced doctoral students may be excused after three years of residence. No degree credit is granted.

**EAEE E9302x and y Mining engineering research**
0–4 pts. Not offered in 2022–2023. Graduate research directed toward solution of technicoscientific problems in mining.

**EAEE E9305x and y–S9305 Earth and environmental engineering research**
0–12 pts. Members of the faculty. Graduate research directed toward solution of a problem in mineral processing or chemical metallurgy.

**EAEE E9800x and y–S9800 Doctoral research instruction**
3, 6, 9, or 12 pts. Members of the faculty. A candidate for the Eng.Sc.D. degree in mineral engineering must register for 12 points of doctoral research instruction. Registration in EAEE E9800 may not be used to satisfy the minimum residence requirement for the degree.

**EAEE E9900x and y–S9900 Doctoral dissertation**
0 pts. Members of the faculty. A candidate for the doctorate may be required to register for this course every term after the student’s coursework has been completed, and until the dissertation has been accepted.
Contemporary is a broad discipline that encompasses a wide range of activities. A common theme is the use of electrical and electromagnetic signals for the generation, transmission, processing, storage, conversion, and control of information and energy. An equally important aspect is the human interface and the role of individuals as the sources and recipients of information. The rates at which information is transmitted today range from megabits per second to gigabits per second and in some cases, as high as terabits per second. The range of frequencies over which these processes are studied extends from direct current (i.e., zero frequency), to microwave and optical frequencies.

The need for increasingly faster and more sophisticated methods of handling information poses a major challenge to the electrical engineer. New materials, information, and data; networking and communications; nanoscale structures, and medical electronics.

The faculty of the Electrical Engineering Department at Columbia University is dedicated to the continued development of further innovations through its program of academic instruction and research. Our undergraduate program in electrical engineering is designed to prepare students for a career in industry, research, or business by providing them with a thorough foundation of the fundamental concepts and analytical tools of contemporary electrical engineering. A wide range of elective courses permits the student to emphasize specific disciplines such as communications, devices, circuits, or signal processing.

Undergraduates have an opportunity to learn firsthand about current research activities by participating in a program of undergraduate research projects with the faculty. A master's level program in electrical engineering permits graduate students to further specialize their knowledge and skills within a wide range of disciplines. For those who are interested in pursuing a career in teaching, research, or advanced development, our Ph.D. program offers the opportunity to conduct research under faculty supervision at the leading edge of technology and applied science. Seminars are offered in all research areas.

The Electrical Engineering Department, along with the Computer Science Department, also offers B.S. and M.S. programs in computer engineering. Details on those programs can be found in the Computer Engineering section in this bulletin.

Research Activities

The research interests of the faculty encompass a number of rapidly growing areas, vital to the development of future technology, that will affect almost every aspect of society: signals, information, and data; networking and communications; nanoscale structures and integrated solid-state devices;
nanoelectronics and nanophotonics; integrated circuits and systems; systems biology; neuroengineering; and smart electric energy. Details on all of these areas can be found at ee.columbia.edu/research.

The Signals, Information and Data area concerns the representation, processing, analysis, and communication of information embedded in signals and datasets arising in a wide range of application areas, including audio, video, images, communications, and biology. Research interests include the development of models, algorithms and analyses for sensing, detection and estimation, statistical and machine learning, and the recognition, organization, and understanding of the information content of signals and data.

The Networking and Communications area focuses on the design and performance evaluation of communication systems and data networks of all kinds, including wireless/cellular, optical, ultra-low power, vehicular, mobile, wearable, data center networks, cyber physical systems, and the internet. Methods range from analyzing and refining existing approaches to the development of new and evolving networking techniques and systems.

The Systems Biology and Neuroengineering area aims to understand and analyze biological systems within the living cell and in the brain. Examples of related tasks are biomolecular data analysis for medical applications, synthetic biology, establishing the principles of neuroinformation processing in the brain for developing robust sensory processing and motor control algorithms, accelerating the clinical translation of devices that make contact with neurons, and building massively parallel brain-computer interfaces.

The Integrated Circuits and Systems area focuses on the integration of circuits and systems on semiconductor platforms. Research spans the analysis, design, simulation, and validation of analog, mixed-mode, (sub) mm-wave, RF, power, and digital circuits, and their applications from computation and sensing to cyber-physical and implantable biomedical systems.

The area of Nanoscale Structures and Integrated Devices applies fundamental physical principles to develop revolutionary new electronic, photonic, and optical devices made from conventional and emerging materials, including graphene, 2D semiconductors, and organic semiconductors. Research includes nanofabrication, characterization, and electromagnetic design of quantum device structures and complex silicon photonic circuits that impact numerous fields from Lidar and optogenetics to low-energy computation and flexible electronics. The smart electric energy area focuses on the optimization of the generation, conversion, distribution, and consumption of electric energy as well as the electrification of energy systems. Research spans the analysis, design, and control of power electronics, motor drive, and energy storage systems, grid resilience and security, and Internet-of-Things. Applications include transportation electrification, smart grid, renewable energy, and smart building systems.

Laboratory Facilities
Current research activities are fully supported by more than a dozen well-equipped research laboratories run by the department faculty. In addition, faculty and students have access to a clean room for micro- and nanofabrication, a materials-characterization facility, and an electron-microscopy facility, managed by the Columbia Nano Initiative. Faculty laboratories include Digital Video and Multimedia Networking Laboratory, Wireless and Mobile Networking Laboratory, Network Algorithms Laboratory, Genomic Information Systems Laboratory, Structure-Function Imaging Laboratory, Neural Acoustic Processing Laboratory, Signal Processing and Communication Laboratory, Translational Neuroelectronics Laboratory, Bionet Laboratory, Molecular Beam Epitaxy Laboratory, Surface Analysis Laboratory, Laboratory for Unconventional Electronics, Advanced Semiconductor Device Laboratory, Motor Drives and Power Electronics Laboratory, Intelligent and Connected Systems Laboratory, Columbia Integrated Systems Laboratory (CISL), Analog & RF IC Design Laboratory, VLSI Design Laboratory, High Speed and mmWave IC Laboratory, Analog and Mixed Signal IC Laboratory, Bioelectronics Laboratory, Lightwave Laboratory, and Nano Photonics Laboratory.

Laboratory instruction is provided in a suite of newly-renovated facilities on the twelfth floor of the S. W. Mudd Building. These teaching laboratories are used for circuit prototyping, device measurement, VLSI design, embedded systems design, as well as computer engineering and Internet-of-Things experiments.

UNDERGRADUATE PROGRAM
The educational objective of the Electrical Engineering program, in support of the mission of the School, is to prepare graduates to achieve success in one or more of the following within a few years after graduation:

1. Graduate or professional studies—as evidenced by admission to a top-tier program, attainment of advanced degrees, research contributions, or professional recognition.
2. Engineering practice—as evidenced by entrepreneurship; employment in industry, government, academia, or nonprofit organizations in engineering; patents; or professional recognition.
3. Careers outside of engineering that take advantage of an engineering education—as evidenced by contributions appropriate to the chosen field.

The Electrical Engineering program will prepare its undergraduates to attain the following:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must
## ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
### EARLY-STARTING STUDENTS

<table>
<thead>
<tr>
<th>Semester</th>
<th>Mathematics</th>
<th>Physics (three tracks, choose one)</th>
<th>Chemistry</th>
<th>Core Required Courses</th>
<th>Required Labs</th>
<th>University Writing</th>
<th>Required NonTechnical Electives</th>
<th>Computer Science</th>
<th>Physical Education</th>
<th>The Art of Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I</strong></td>
<td>MATH UN1101 (3)</td>
<td>UN1401 (3)</td>
<td>one-semester lecture (3–4)</td>
<td>ELEN E1201 (3.5)</td>
<td>ELEN E3081 (1)</td>
<td>CC1010 (3)</td>
<td>HUMA CC1001, COCI CC1101, or Global Core (3–4); HUMA UN1121 or UN1123 (3); HUMA CC1102, COCI CC1102, or Global Core (3–4); ECON UN1105 (4) and UN1155 recitation (0); some of these courses can be postponed to the junior or senior year, to make room for taking the above electrical engineering courses.</td>
<td>ENGI E1006 (3)</td>
<td>UN1001 (!)</td>
<td>ENGI E1102 (4) either semester</td>
</tr>
<tr>
<td><strong>II</strong></td>
<td>MATH UN1102 (3)</td>
<td>UN1402 (3)</td>
<td>UN1403 or UN1404 or UN2045 or UN1604</td>
<td>ELEN E3201 (3.5)</td>
<td>Circuit analysis lab</td>
<td></td>
<td></td>
<td></td>
<td>UN1002 (!)</td>
<td></td>
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<tr>
<td><strong>III</strong></td>
<td>APMA E2000 (4) and E2001 (0) either semester</td>
<td>UN1601 (3.5)</td>
<td>ELEN E3801 (3.5)</td>
<td>Circuit analysis</td>
<td>ELEN E3083 (1)</td>
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<tr>
<td><strong>IV</strong></td>
<td>and APMA E2101 (3)</td>
<td>UN2801 (4.5)</td>
<td>Signals and systems</td>
<td>ELEN E3801 (3.5)</td>
<td>Circuit analysis</td>
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<tr>
<td><strong>II</strong></td>
<td>UN1602 (3.5)</td>
<td>UN2802 (4.5)</td>
<td>ELEN E3801 (3.5)</td>
<td>Signals and systems</td>
<td>ELEN E3084 (1)</td>
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<tr>
<td><strong>IV</strong></td>
<td>UN1602 (3.5)</td>
<td>UN2802 (4.5)</td>
<td>ELEN E3801 (3.5)</td>
<td>Signals and systems</td>
<td>ELEN E3082 (1)</td>
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</tbody>
</table>

### Notes:

1. APMA E2101 may be replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010.
2. If possible, these labs should be taken along with their corresponding lecture courses.
3. ENGI E1006 may not be offered every semester. See ee.columbia.edu for more discussion about the Computer Science sequences.

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consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on teams whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

The B.S. program in electrical engineering at Columbia University seeks to provide a broad and solid foundation in the current theory and practice of electrical engineering, including familiarity with basic tools of math and science, an ability to communicate ideas, and a humanities background sufficient to understand the social implications of engineering practice. Graduates should be qualified to enter the profession of
### Electrical Engineering: Third and Fourth Years

#### Early-Starting Students

<table>
<thead>
<tr>
<th>Semester V</th>
<th>Semester VI</th>
<th>Semester VII</th>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physics</strong> (tracks continued)</td>
<td>UN1403 (3)</td>
<td>ELEN E3401 (4)</td>
<td>ELEN E3390 (3)$^1$</td>
</tr>
<tr>
<td></td>
<td>UN2601 (3.5)</td>
<td>ELEN E3701 (3)$^2$</td>
<td></td>
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<tr>
<td></td>
<td>Lab W3081 (2)</td>
<td>Intro. to communication systems or CSEE W4119 (3)$^2$</td>
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</tr>
<tr>
<td><strong>EE Core Required Courses</strong></td>
<td>ELEN E3106 (3.5)</td>
<td>ELEN E3043 (3)</td>
<td>Lab UN1494 (3)$^1$</td>
</tr>
<tr>
<td></td>
<td>Solid-state devices and materials</td>
<td>Solid state, microwave, and fiber optics lab</td>
<td></td>
</tr>
<tr>
<td><strong>EE Required Labs</strong></td>
<td>ELEN E3401</td>
<td>ELEN E3399 (1)</td>
<td>ELEN E3399 (1)</td>
</tr>
<tr>
<td></td>
<td>Lab W3081 (2)</td>
<td>EE practice</td>
<td>Capstone design course</td>
</tr>
<tr>
<td><strong>Other Required Courses</strong></td>
<td>IEOR E3658 or STAT GU4203$^4$, and COMS W3136 (or W3134 or W3137)$^5$</td>
<td>(some of these courses are not offered both semesters. Students with an adequate background can take some of these courses in the sophomore year)</td>
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</tr>
<tr>
<td><strong>EE Depth Tech</strong></td>
<td>At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking (for details, see ee.columbia.edu)</td>
<td>(at least 6 points total)</td>
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<tr>
<td></td>
<td>(at least 6 points total)</td>
<td>At least two technical electives outside the chosen depth area; must be courses with significant engineering content (see ee.columbia.edu)</td>
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<tr>
<td><strong>Electives</strong></td>
<td>Additional technical electives (consisting of more depth or breadth courses, or further options listed at ee.columbia.edu/ee-undergraduate-program) as required to bring the total points of technical electives to 18$^6$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other Tech</strong></td>
<td></td>
<td>Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement) or seas.columbia.edu for details (administered by the advising dean)</td>
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</tr>
<tr>
<td><strong>NonTech</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Points</strong>$^7$</td>
<td>16.5</td>
<td>17</td>
<td>16</td>
</tr>
</tbody>
</table>

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1. Chemistry lab (CHEM UN1500) may be substituted for physics lab, although this is not generally recommended.
2. These courses can be taken in the sophomore year if the prerequisites/corequisites are satisfied.
3. The capstone design course provides ELEN majors with a “culminating design experience.” As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.
4. SIEO W3600 and STAT GU4001 cannot generally be used to replace IEOR E3658 or STAT GU4203.
5. Students who plan to minor in Computer Science should choose COMS W3134 or W3137.
6. The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can also apply for this waiver, but the courses must have been at an advanced level for this to be considered.
7. “Total points” assumes that 20 points of nontechnical electives and other courses are included.
Engineering, to continue toward a career in engineering research, or to enter other fields in which engineering knowledge is essential. Required nontechnical courses cover civilization and culture, philosophy, economics, and a number of additional electives. English communication skills are an important aspect of these courses. Required science courses cover basic chemistry and physics, whereas math requirements cover calculus, differential equations, probability, and linear algebra. Basic computer knowledge is also included, with an introductory course on using engineering workstations and two rigorous introductory computer science courses. Core electrical engineering courses cover the main components of modern electrical engineering and illustrate basic engineering principles. Topics include a sequence of two courses on circuit theory and electronic circuits, one course on semiconductor devices, one on electromagnetics, one on signals and systems, one on digital systems, and one on communications or networking. Engineering practice is developed further through a sequence of laboratory courses, starting with a first-year course to introduce hands-on experience early and to motivate theoretical work. Simple creative design experiences start immediately in this first-year course. Following this is a sequence of lab courses that parallel the core lecture courses, often coupled with experimentation and

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ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
LATE-STARTING STUDENTS

<table>
<thead>
<tr>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATHEMATICS</strong></td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0) either semester</td>
</tr>
<tr>
<td><strong>PHYSICS</strong></td>
<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>UN1403 (3)</td>
</tr>
<tr>
<td>(three tracks, choose one)</td>
<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td>UN2601 (3.5)</td>
</tr>
<tr>
<td></td>
<td>UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
<td>Lab UN3081 (2)</td>
</tr>
<tr>
<td><strong>CHEMISTRY</strong></td>
<td>one-semester lecture (3–4)</td>
<td>UN1403 (3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UN1403 or UN1404 or UN2045 or UN1604</td>
<td>UN2601 (3.5)</td>
<td></td>
</tr>
<tr>
<td><strong>ELECTRICAL ENGINEERING</strong></td>
<td>ELEN E1201 (3.5) either semester³</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
<td>CC1010 (3) either semester</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
<td>HUMA CC1001, COCI CC1101, or Global Core (3–4)</td>
<td>HUMA CC1002, COCI CC1102, or Global Core (3–4)</td>
<td>ECON UN1105 (4) and UN1155 recitation (0)</td>
</tr>
<tr>
<td><strong>COMPUTER SCIENCE</strong></td>
<td>ENGI E1006 (3) any semester⁴</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PHYSICAL EDUCATION</strong></td>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
<td></td>
</tr>
<tr>
<td><strong>THE ART OF ENGINEERING</strong></td>
<td>ENGI E1102 (4) either semester</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ APMA E2101 may be replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010.
² Chemistry lab (CHEM UN1500) may be substituted for physics lab, although this is not generally recommended.
³ Transfer students and 3-2 Combined Plan students who have not taken ELEN E1201 prior to the junior year are expected to have taken a roughly equivalent course when they start ELEN E3201.
⁴ ENGI E1006 may not be offered every semester. See ee.columbia.edu for more discussion about the Computer Science sequences.
## Electrical Engineering: Third and Fourth Years

### Late-Starting Students

<table>
<thead>
<tr>
<th>Semester V</th>
<th>Semester VI</th>
<th>Semester VII</th>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EE Core Required Courses</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3106 (3.5) Solid-state devices and materials</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ELEN E3201 (3.5) Circuit analysis</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ELEN E3801 (3.5) Signals and systems</td>
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<tr>
<td>CSEE W3827(3) Fund. of computer sys.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ELEN E3331 (3) Electronic circuits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3401 (4) Electromagnetics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3701 (3) Intro. to communication systems or CSEE W4119 (3) Computer networks</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Semester VI</th>
<th>Semester VII</th>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EE Required Labs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3081 (1)' Circuit analysis lab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3084 (1)' Signals and systems lab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3083 (1)' Electronic circuits lab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3082 (1)' Digital systems lab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3043 (3) Solid state, microwave, and fiber optics lab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3399 (1) EE practice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3390 (3)² Capstone design course</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semester VII</th>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Other Required Courses</strong></td>
<td></td>
</tr>
<tr>
<td>IEOR E3658 or STAT GU4203³; and COMS W3136 (or W3134 or W3137)⁴ (Some of these courses are not offered both semesters)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electives</strong></td>
</tr>
<tr>
<td><strong>EE Depth Tech</strong></td>
</tr>
<tr>
<td>At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. (For details, see ee.columbia.edu.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Breadth Tech</strong></td>
</tr>
<tr>
<td>(at least 6 points total)</td>
</tr>
<tr>
<td>At least two technical electives outside the chosen depth area; must be courses with significant engineering content (see ee.columbia.edu)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Other Tech</strong></td>
</tr>
<tr>
<td>Additional technical electives (consisting of more depth or breadth courses, or further options listed at ee.columbia.edu/ee-undergraduate-program) as required to bring the total points of technical electives to 18⁵</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NonTech</strong></td>
</tr>
<tr>
<td>Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement) or seas.columbia.edu for details (administered by the advising dean)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semester VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Points</strong>⁶</td>
</tr>
<tr>
<td>15.5</td>
</tr>
</tbody>
</table>

### Note

- This chart shows one possible schedule for a student who takes most of their major program in the final two years. Please refer to the previous chart for a recommended earlier start.
- If possible, these labs should be taken along with their corresponding lecture courses.
- The capstone design course provides ELEN majors with a “culminating design experience.” As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.
- SIEO W3600 and STAT GU4001 cannot generally be used to replace IEOR E3658 or STAT GU4203.
- Students who plan to minor in Computer Science should choose COMS W3134 or W3137.
- The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can also apply for this waiver, but the courses must have been at an advanced level for this to be considered.
- “Total points” assumes that 9 points of nontechnical electives are included.

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1 If possible, these labs should be taken along with their corresponding lecture courses.
2 The capstone design course provides ELEN majors with a “culminating design experience.” As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.
3 SIEO W3600 and STAT GU4001 cannot generally be used to replace IEOR E3658 or STAT GU4203.
4 Students who plan to minor in Computer Science should choose COMS W3134 or W3137.
5 The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can also apply for this waiver, but the courses must have been at an advanced level for this to be considered.
6 “Total points” assumes that 9 points of nontechnical electives are included.
computer simulation, respectively. The culmination of the laboratory sequence and the design experiences introduced throughout earlier courses is a senior design course (capstone design course), which includes a significant design project that ties together the core program, encourages creativity, explores practical aspects of engineering practice, and provides additional experience with communication skills in an engineering context. Finally, several technical electives are required, chosen to provide both breadth and depth in a specific area of interest. More detailed program objectives and outcomes are posted at ee.columbia.edu.

The program in electrical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET, http://www.abet.org.

There is a strong interaction between the Department of Electrical Engineering and the Departments of Computer Science, Applied Physics and Applied Mathematics, Industrial Engineering and Operations Research, Physics, and Chemistry.

**EE Core Curriculum**

All electrical engineering (EE) students must take a set of core courses, which collectively provide the student with fundamental skills, expose them to the breadth of EE, and serve as a springboard for more advanced work, or for work in areas not covered in the core. These courses are shown on the charts in Undergraduate Degree Tracks. A full curriculum checklist is also posted at ee.columbia.edu.

**Technical Electives**

The 18-point technical elective requirement for the electrical engineering program consists of three components: depth, breadth, and other. A general outline is provided here, and more specific course restrictions can be found at ee.columbia.edu. For any course not clearly listed there, adviser approval is necessary.

The depth component must consist of at least 6 points of electrical engineering courses in one of four defined areas: (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. The depth requirement provides an opportunity to pursue particular interests and exposure to the process of exploring a discipline in depth—an essential process that can be applied later to other disciplines, if desired.

The breadth component must consist of at least 6 additional points of courses that are outside of the chosen depth area and have significant engineering content. These courses can be from other departments within the School. The breadth requirement precludes overspecialization. Breadth is particularly important today, as innovation requires more and more of an interdisciplinary approach, and exposure to other fields is known to help one’s creativity in one’s own main field. Breadth also reduces the chance of obsolescence as technology changes.

Any remaining technical elective courses, beyond the minimum 12 points of depth and breadth, do not have to be engineering courses (except for students without ELEN E1201 or approved transfer credit for ELEN E1201) but must be technical. Generally, math and science courses that do not overlap with courses used to fill other requirements are allowed.

If another department advertises that one of their courses can be used as a technical elective, that does not necessarily mean it will be approved as a technical elective in the electrical engineering program. Which courses are approved depends on other electives chosen due to the depth and breadth restrictions, and the need for sufficient engineering and technical content within the entire 18 points. Electrical engineering technical electives must also be 3000-level or above and must not have significant overlap with other courses taken for the major.

**Starting Early**

The EE curriculum is designed to allow students to start their study of EE in their first year. This motivates students early and allows them to spread nontechnical requirements more evenly. It also makes evident the need for advanced math and physics concepts, and motivates the study of such concepts. Finally, it allows more time for students to take classes in a chosen depth area, or gives them more time to explore before choosing a depth area. Students can start with ELEN E1201: Introduction to electrical engineering in the second semester of their first year, and can continue with other core courses one semester after that, as shown in the “early-starting students” chart. It is emphasized that both the early- and late-starting sample programs shown in the charts are examples only; schedules may vary depending on student preparation and interests.

**Transfer Students**

Transfer students coming to Columbia as juniors with sufficient general background can complete all requirements for the B.S. degree in electrical engineering. Such students fall into one of two categories:

**Plan 1:** Students coming to Columbia without having taken the equivalent of ELEN E1201 must take this course in their junior year. This requires postponing the core courses in circuits and electronics until the senior year, and thus does not allow taking electives in that area; thus, such students cannot choose circuits and electronics as a depth area.

**Plan 2:** This plan is for students who have taken a course equivalent to ELEN E1201 at their school of origin, including a laboratory component. See the bulletin for a description of this course. Many pre-engineering programs and physics departments at four-year colleges offer such courses. Such students can start taking circuits at Columbia immediately, and thus can choose circuits and electronics as a depth area.

It is stressed that ELEN E1201 or its equivalent is a key part of the EE curriculum. The preparation provided by this course is essential for a number of other core courses.

Sample programs for both Plan 1 and Plan 2 transfer students can be found at ee.columbia.edu.

**B.S./M.S. Program**

The B.S./M.S. degree program is open to a select group of undergraduate students. This double degree program makes possible the earning of both
the Bachelor of Science and Master of Science degrees in an integrated fashion. Up to 6 points may be credited to both degrees, and some graduate classes taken in the senior year may count toward the M.S. degree. Interested students can find further information at ee.columbia.edu and can discuss options directly with their faculty adviser. Students must be admitted prior to the start of their seventh semester at Columbia Engineering. Students in the 3-2 Combined Plan undergraduate program are not eligible for admission to this program.

**GRADUATE PROGRAMS**

The Department of Electrical Engineering offers graduate programs leading to the degree of Master of Science (M.S.) and the degrees of Doctor of Engineering Science (Eng. Sc.D.) and Doctor of Philosophy (Ph.D.). The Graduate Record Examination (General Test only) is required of all applicants except special students. An undergraduate grade-point average equivalent to B or better from an institution comparable to Columbia is expected.

Applicants who, for good reasons, are unable to submit GRE test results by the deadline date but whose undergraduate record is clearly superior may file an application without the GRE scores. An explanatory note should be added to ensure that the application will be processed even while incomplete. If the candidate’s admissibility is clear, the decision may be made without the GRE scores; otherwise, it may be deferred until the scores are received.

There are no prescribed course requirements in any of the regular graduate degree programs. Students, in consultation with their faculty advisers, design their own programs, focusing on particular fields of electrical engineering. Among the fields of graduate study are Communications, Networking, Internet and Internet of Things; Computer Engineering; Integrated Circuits and Systems and Electronics; Integrated Devices and Photonics; Signals, Information, Data, Learning and Control; Smart Electric Energy; and Systems Biology and Neuroengineering.

Graduate course charts for several focus areas can be found at ee.columbia.edu.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–E6004 and should consult their program for specific PDL requirements.

**Master of Science Degree**

Candidates for the M.S. degree in electrical engineering must complete 30 points of credit beyond the bachelor’s degree. A minimum of 15 points of credit must be at the 6000 level or higher. No credit will be allowed for undergraduate courses (3000 or lower). At least 15 points must be in electrical engineering, defined as including all courses with an ELEN designator or a joint designator containing electrical engineering as a member, e.g., EECS, CSEE, EEME, ECBM, etc. And it is expected that at least 12 of the first 24 points taken will be in electrical engineering.

Not all technical courses can be applied toward the M.S. degree, and some have restrictions. Up to 6 points of research (such as ELEN E4998, ELEN E6001, and ELEN E6002) can be applied. Up to 1.5 points of fieldwork (ELEN E6999) can be used. No more than 3 points of courses that do not contain primarily engineering, math, or science content can be used, subject to the written pre-approval of the department. Any course that is not on the list of standard courses specified at ee.columbia.edu/masters-program requires prior written department approval, including during the summer session.

The general school requirements listed earlier in this bulletin, such as minimum GPA, must also be satisfied. All degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

More details and a requirements checklist for approvals can be found at ee.columbia.edu/masters-program.

**Doctoral Degree**

The requirements for the Ph.D. and Eng. Sc.D. degrees are identical. Both require a dissertation based on the candidate’s original research, conducted under the supervision of a faculty member. The work may be theoretical or experimental or both.

Students who wish to become candidates for the doctoral degree in electrical engineering have the option of applying for admission to the Eng.Sc.D. program or the Ph.D. program. Students who elect the Eng.Sc.D. degree register in the School of Engineering and Applied Science; those who elect the Ph.D. degree register in the Graduate School of Arts and Sciences.

Doctoral candidates must obtain a minimum of 60 points of formal course credit beyond the bachelor’s degree. A master’s degree from an accredited institution may be accepted as equivalent to 30 points. A minimum of 30 points beyond the master’s degree must be earned while in residence in the doctoral program.

More detailed information regarding the requirements for the doctoral degree may be obtained in the department office and at ee.columbia.edu.

**Optional M.S. Specializations**

Students in the electrical engineering M.S. program often choose to use some of their electives to focus on a particular field. Students may pick one of a number of optional, formal specialization templates or design their own M.S. program in consultation with an adviser. These specializations are not degree requirements. They represent suggestions from the faculty as to how one might fill one’s programs so as to focus on a particular area of interest. Students may wish to follow these suggestions, but they need not. The degree requirements are quite flexible and are listed in the Master of Science Degree section, above. All students, whether following a formal specialization template or not, are expected to include breadth in their program. Not all of the elective courses listed here are offered every year. For the latest information on available courses, visit the Electrical Engineering home page at ee.columbia.edu.

**Specialization in Data-Driven Analysis and Computation**

Advisers: Professors Dimitris
1. Satisfy M.S. degree requirements.
2. Take at least two courses from ECBM E4040: Neural networks and deep learning; EECS E4764: Internet of things—intelligent and connected systems; ELEN E4810: Digital signal processing; ELEN E4720: Machine learning for signals, information, and data; EEOR E6616: Convex optimization; ECES E6893: Topic: big data analytics.
3. Take at least one courses from ECBM E6040: Neural networks and deep learning research; EECS E6720: Bayesian models for machine learning; EECS E6765: Internet of things—systems and physical data analytics; EES E6895: Topic: advanced big data analytics.
4. Take a second course from #3 or one course from ECBM E4060: Introduction to genomic information science and technology; ECBM E4070; ECBM: E607x: Topics in neuroscience and deep learning; ELEN E6690: Topics in data-driven analysis and computation; ELEN E6876: Sparse and low-dimensional models for high-dimensional data; ELEN E9601: Seminar in data-driven analysis and computation.

Specialization in Networking
Advisers: Professors Predrag Jelenkovic, Javad Ghaderi, Ethan Katz-Bassett, Debasis Mitra, Gil Zussman, Xiaofan (Fred) Jiang

1. Satisfy M.S. degree requirements.
2. One basic networking course from the following: ELEN E6761: Computer communication networks I; CSEE W4119: Computer networks.
3. One basic systems or analytical course from the following:
4. Three courses from the following list (courses cannot be used to fulfill both this requirement and any of the above requirements): ELEN E6488: Optical interconnects and interconnection networks; ELEN E6761: Computer communication networks I; ELEN E6767: Internet economics, energy, and society; ELEN E6770: Topic: next generation networks; ELEN E6772: Topic: network algorithms; ELEN E6775: Topic: computer networks: a systems approach; ELEN E6776: Topic: content distribution networks; ELEN E6950: Wireless and mobile networking I; EEOR E4650: Convex optimization for EE; EEOR E6616: Convex optimization; CSEE E4140: Networking laboratory; EENS E4951: Wireless networks and systems; CSEE E6180: Modeling and Performance Evaluation; COMS W4180: Network security; COMS W4995: Internet technology, economics, and policy, COMS E618: Advanced internet services; COMS E6998: Cloud computing and big data; IOR E6704: Queueing theory; IEOR E4106: Stochastic models; with adviser approval, other relevant advanced topic courses on networking topics from ELEN E677x, COMS W4995, COMS E6998, or other course numbers may be used to fulfill this requirement.
5. At least two of the four courses used to fulfill requirements 3 and 4 must be 6000-level ELEN, EES, CSEE, or EEOR courses.

Specialization in Wireless and Mobile Communications
Advisers: Professors Gil Zussman, Predrag Jelenkovic, Xiaodong Wang

1. Satisfy M.S. degree requirements.
2. One basic circuits course such as: ELEN E4312: Analog electric circuits; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6312: Advanced analog ICs.
3. Two communications or networking courses such as: CSEE W4119: Computer networks; ELEN E4702: Digital communications; ELEN E4703: Wireless communications; ELEN E6711: Stochastic communications and noise; ELEN E4810: Digital signal processing; ELEN E6950: Wireless and mobile networking, I; EECS E4951: Wireless network and systems; ELEN E6761: Computer communication networks, I; ELEN E6712: Communication theory; ELEN E6713: Topics in communications; ELEN E6717: Information theory; ELEN E677x: Topics in telecommunication networks.
4. At least two additional approved courses in wireless communications or a related area.

Specialization in Integrated Circuits and Systems
Advisers: Professors Peter Kinget, Harish Krishnaswamy, Mingoo Seok, Kenneth Shepard, Yannis Tsividis, Charles Zukowski

1. Satisfy M.S. degree requirements.
3. One analog course from ELEN E4312: Analog electronic circuits; ELEN E6312: Advanced analog integrated circuits; ELEN E6316: Analog digital interfaces in VLSI; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6320: Millimeter-wave IC design.
4. Two additional courses such as other courses from no. 2 and 3; ELEN E6350: VLSI design laboratory; ELEN E6304: Topics in electronic circuits; ELEN E6315: Microwave circuit design; ELEN E9303: Seminar in electronic circuits.
5. At least one additional approved course in integrated circuits and systems or a related area.

Specialization in Smart Electric Energy
Advisers: Professors Matthias Preindl, Xiaofan (Fred) Jiang, Gil Zussman, Kenneth Shepard, Xiaodong Wang

1. Satisfy M.S. degree requirements.
2. Take at least two power conversion or power systems courses from:
Specialization in Systems Biology and Neuroengineering
Advisers: Professors Dimitris Anastassiou, Christine Hendon, Pedrag Jelenkovic, Aurel A. Lazar, Nima Mesgarani, Kenneth Shepard, Xiaodong Wang

Specialization in Lightwave (Photonics) Engineering
Advisers: Professors Keren Bergman, Ioannis (John) Kymissis, Michal Lipson

1. Satisfy M.S. degree requirements.
2. Take both ECBM E4060: Introduction to genomic information science and technology and BMEB W4020: Computational neuroscience, circuits in the brain.
3. Take at least one course from BMEE E4030: Neural control engineering; ECBM E4040: Neural networks and deep learning; ECBM E4070; ECBM E4090: Brain computer interfaces (BCI) laboratory, CBMF W4761: Computational genomics; ELEN E6010: Systems biology: design principles for biological circuits; EEBM E6020: Methods in computational neuroscience; BMEE E6030: Neural modeling and neuroengineering.
4. Take at least one course from ECBM E6040: Neural networks and deep learning research; ECBM E607x: Topics in neuroscience and deep learning; ELEN E608x: Topics in systems biology; EEBM E609x: Topics in computational neuroscience and neuroengineering; ELEN E6261: Computational methods of circuit analysis ELEN E6717: Information theory; ELEN E6860: Advanced digital signal processing.

Specialization in Microelectronic Devices
Advisers: Professors Dion Khodagholy, Ioannis (John) Kymissis, Michal Lipson, James Teherani, Wen Wang

1. Satisfy M.S. degree requirements.
2. One basic course such as: ELEN E4301: Introduction to semiconductor devices or ELEN E4411: Fundamentals of photonics.
4. At least two other approved courses in devices or a related area. Options also include courses outside EE such as APPH E4090: Nanotechnology; APPH E4100: Quantum physics of matter; APPH E4110: Modern optics; CHAP E4120: Statistical mechanics; APPH E4140: Physics of solar energy; APPH E6081: Solid state physics, I; APPH E6082: Solid state physics, II; APPH E6091: Magnetism and magnetic materials; APPH E6110: Laser interactions with matter; MSAE E4202: Thermodynamics and reactions in solids; MSAE E4206: Electronic and magnetic properties of solids; MSAE E4207: Lattice vibrations and crystal defects; MSAE E6120: Grain boundaries and interfaces; MSAE E6220: Crystal physics; MSAE E6229: Energy and particle beam processing of materials; MSAE E6225: Techniques in X-ray and neutron diffraction.
COURSES IN ELECTRICAL ENGINEERING

ELEN E1101x or y The digital information age
3 pts. Lect: 3. Professor Vallancourt.
An introduction to information transmission and storage, including technological issues. Binary numbers; elementary computer logic; digital speech and image coding; basics of compact disks, telephones, modems, faxes, UPC bar codes, and the World Wide Web. Projects include implementing simple digital logic systems and Web pages. Intended primarily for students outside the School of Engineering and Applied Science. The only prerequisite is a working knowledge of elementary algebra.

ELEN E1201x and y Introduction to electrical engineering
3.5 pts. Lect: 3. Lab:1. Professor Vallancourt.
Prerequisite(s): MATH UN1101. Basic concepts of electrical engineering. Exploration of selected topics and their application. Electrical variables, circuit laws, nonlinear and linear elements, ideal and real sources, transducers, operational amplifiers in simple circuits, external behavior of diodes and transistors, first order RC and RL circuits. Digital representation of a signal, digital logic gates, flip-flops. A lab is an integral part of the course. Required of electrical engineering and computer engineering majors.

ELEN E3043x Solid state, microwave, and fiber optics laboratory
Prerequisite(s): ELEN E3106 and ELEN E3401. Optical electronics and communications. Microwave circuits. Physical electronics.

ELEN E3081x Circuit analysis laboratory
1 pt. Lab: 3. Professor Zukowski.
Prerequisite(s): ELEN E1201 or equivalent. Corequisite(s): ELEN E3201. Companion lab course for ELEN E3201. Experiments cover such topics as: use of measurement instruments; HSPICE simulation; basic network theorems; linearization of nonlinear circuits using negative feedback; op-amp circuits; integrators; second order RLC circuits. The lab generally meets on alternate weeks.

ELEN E3082y Digital systems laboratory
1 pt. Lab: 3. Professor Shepard.
Corequisite(s): CSEE W3827. Recommended preparation: ELEN E1201 or equivalent. Companion lab course for CSEE W3827. Experiments cover such topics as logic gates; flip-flops; shift registers; counters; combinational logic circuits; sequential logic circuits; programmable logic devices. The lab generally meets on alternate weeks.

ELEN E3083y Electronic circuits laboratory
1 pt. Lab: 3. Professor Vallancourt.
Prerequisite(s): ELEN E3081. Corequisite(s): ELEN E3331. Companion lab course for ELEN E3331. Experiments cover such topics as macromodeling of nonidealities of opamps using SPICE, Schmitt triggers and astable multivibrations using opamps and diodes; logic inverters and amplifiers using bipolar junction transistors; logic inverters and ring oscillators using MOSFETs; filter design using opamps. The lab generally meets on alternate weeks.

ELEN E3084x Signals and systems laboratory
Corequisite(s): ELEN E3081. Companion lab course for ELEN E3081. Experiments cover topics such as: introduction and use of MATLAB for numerical and symbolic calculations; linearity and time invariance; continuous-time convolution; Fourier-series expansion and signal reconstruction; impulse response and transfer function; forced response. The lab generally meets on alternate weeks.

ELEN E3106x Solid-state devices and materials
Prerequisite(s): MATH UN1201 or APMA E2000 or equivalent. Corequisite(s): PHYS UN1403 or PHYS UN2601 or equivalent. Crystal structure and energy band theory of solids. Carrier concentration and transport in semiconductors. P-n junction and junction transistors. Semiconductor surface and MOS transistors. Optical effects and optoelectronic devices. Fabrication of devices and the effect of process variation and distribution statistics on device and circuit performance.

ELEN E3201x Circuit analysis

ELEN E3331y Electronic circuits
3 pts. Lect: 3. Professor Zukowski.

ELEN E3390y Electrical engineering senior design project
3 pts. Lab: 6. Professor Vallancourt.
Prerequisite(s): ELEN E3399 and completion of most other required EE courses. Students work in teams to specify, design, implement and test an engineering prototype. Involves technical as well as non-technical considerations, such as manufacturability, impact on the environment, economics, engineering standards, and other real-world constraints. Projects are presented publicly by each design team in a school-wide expo.

ELEN E3399x Electrical engineering practice
1 pt. Professor Vallancourt.
Design project planning, written and oral technical communication, the origin and role of standards, engineering ethics, and practical aspects of engineering as a profession, such as career development and societal and environmental impact. Generally taken senior year just before ELEN E3390.

ELEN E3401y Electromagnetics
4 pts. Lect: 3. Professor Bergman.
Prerequisite(s): MATH UN1201 or APMA E2000, PHYS UN1402 or PHYS UN1602, or equivalents. Basic field concepts. Interaction of time-varying electromagnetic fields. Field calculation of lumped circuit parameters. Transition from electrostatic to quasistatic and electromagnetic regimes. Transmission lines. Energy transfer, dissipation, and storage. Waveguides. Radiation.

EEME E3601x Classical control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite(s): MATH UN2030. Analysis and design of feedback control systems. Transfer functions; block diagrams; proportional, rate, and integral controllers; hardware; implementation. Routh stability criterion, root locus, Bode and Nyquist plots, compensation techniques.

ELEN E3701y Introduction to communication systems
3 pts. Lect: 3. Professor Kalet.
Prerequisite(s): ELEN E3801. Corequisite(s): IENG E3658. A basic course in communication theory, stressing modern digital communication systems. Nyquist sampling, PAM and PCM/ΔΣM systems, time division multiplexing, high frequency digital (ASK, OOK, FSK, PSK) systems, and AM and FM systems. An introduction to noise processes, detecting signals in the presence of noise, Shannon's theorem on channel capacity, and elements of coding theory.

ELEN E3801x Signals and systems
3.5 pts. Lect: 3. Professor X. Wang.

CSEE W3827x and y Fundamentals of computer systems
3 pts. Lect: 3. Professor Kim.
Prerequisite(s): An introductory programming course. Fundamentals of computer organization and digital logic. Boolean algebra, Karnough maps, basic gates and components, flip-flops and latches, counters and state machines, basics of combinational and sequential digital design. Assembly language, instruction sets, ALUs, single-cycle and multicycle processor design, introduction to pipelined processors, caches, and virtual memory.

ELEN E3990x, y or s Fieldwork
1–2 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used for degree credit. Only for Electrical Engineering and Computer Engineering undergraduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation required. May not be used as technical or nontechnical electives or to satisfy any other Electrical Engineering or Computer Engineering major requirements. May not be taken for pass/fail credit or audited.

ELEN E3998x and y Projects in electrical engineering
0 to 3 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

BMEB W4020x Computational neuroscience: circuits in the brain
3 pts. Lect: 3. Professor Lazar.
Prerequisite(s): ELEN E3801 or BIOL UN3004. The biophysics of computation: modeling biological neurons, the Hodgkin-Huxley neuron, modeling channel conductances and synapses as memristive systems, bursting neurons and central pattern generators, I/O equivalence and spiking neuron models. Information representation and neural encoding: stimulus representation with time encoding machines, the geometry of time encoding, encoding with neural circuits with feedback, population time encoding machines. Dendritic computation: elements of spike processing and neural computation, synaptic plasticity and learning algorithms, unsupervised learning and spike time-dependent plasticity, basic dendritic integration. Projects in MATLAB.

ECBM E4040x or y Neural networks and deep learning
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): BMEB W4020 or BMEE E4030 or ECBM E4090 or ELEN E4750 or COMS W4771 or an equivalent. Developing features and internal representations of the world, artificial neural networks, classifying handwritten digits with logistic regression, feedforward deep networks, back propagation in multilayer perceptrons, regularization of deep or distributed models, optimization for training deep models, convolutional neural networks, recurrent and recursive neural networks, deep learning in speech, and object recognition.

ECBM E4060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Cheng.
Introduction to computational biology with emphasis on genomic data science tools and methodologies for analyzing data, such as genomic sequences, gene expression measurements and the presence of mutations. Applications of machine learning and exploratory data analysis for predicting drug response and disease progression. Latest technologies related to genomic information, such as single-cell sequencing and CRISPR, and the contributions of genomic data science to the drug development process.

ECBM E4070y Computing with brain circuits of model organisms
3 pts. Lect: 3. Professor Lazar.

ECBM E4090x or y Brain computer interfaces (BCI) laboratory
3 pts. Lect: 2. Lab: 3. Professor Mesgarani.

ELEN E4106x Advanced solid state devices and materials
3 pts. Lect: 2.5. Lab: 1. Professor Kymissis.
Prerequisite(s): APMA E2000 and Math UN1201. Corequisites: PHYS UN1403 and UN2601. Crystal structure and energy band theory of solids. Carrier concentration and transport in semiconductors. P-n junction and junction transistors. Semiconductor surface and MOS transistors. Optical effects and optoelectronic devices. Fabrication of devices and the effect of process variation and distribution statistics on device and circuit performance. Course shares lectures with ELEN E3106, but the work requirements differ. Undergraduate students are not eligible to register.

CSEE W4119x and y Computer networks
3 pts. Lect: 3. Professor Rubenstein.
Corequisite(s): IOR E3658 or SIEO W3600 or equivalents. Introduction to computer networks and the technical foundations of the internet, including applications, protocols, local area networks, algorithms for routing and congestion control, security, elementary performance evaluation. Several written and programming assignments required.

CSEE W4121y Computer systems for data science
3 pts. Lect: 3. Professor Cidon.
Prerequisite(s): Background in Computer System Organization and good working knowledge of C/ C++. Corequisite(s): CSOR W4246, STAT GU4203, or equivalent approved by faculty adviser. Introduction to computer distributed systems with emphasis on warehouse scale computing systems. Topics include fundamental tradeoffs in computer systems, hardware and software techniques for exploiting instruction-level parallelism, data-level parallelism and task level parallelism, scheduling, caching, prefetching, network and memory architecture, latency and throughput optimizations, specializations, and introduction to programming data center computers.

CSEE W4140x or y Networking laboratory
3 pts. Lect: 3. Professor Zussman.
Prerequisite(s): CSEE W4119 or equivalent. In this course, students learn how to put “principles into practice,” in a hands-on-networking lab course. The technologies and protocols of the internet are covered, using equipment currently available to large internet service providers such as CISCO routers and end-systems. A set of laboratory experiments provides hands-on experience with engineering wide-area networks and familiarizes students with the Internet Protocol (IP), Address Resolution Protocol (ARP), Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), the Domain Name System (DNS), routing protocols (RIP, OSPF, BGP), network management protocols (SNMP), and application-level protocols (FTP, TELNET, SMTP).

ELEN E4193x or y Modern display science and technology
3 pts. Lect: 3. Professor Kymissis.
Prerequisite(s): Linear algebra, differential equations, and basic semiconductor physics. Introduction to modern display systems in an engineering context. The basis for visual perception, image representation, color space, metrics of illumination. Physics of luminescence, propagation and manipulation of light in anisotropic media, emissive displays, and spatial light modulators. Fundamentals of display addressing, the Alt-Pleshko theorem, multiple line addressing. Large area electronics, fabrication, and device integration of commercially important display types. A series of short laboratories will reinforce material from the lectures. Enrollment may be limited.

EEEL E4220x Energy system economics and optimization
3 pts. Lect: 3. Professor Xu.
Prerequisite(s): Basic linear algebra, basic probability and statistics, and basic programming skills. Fundamental of power system economics over which the current electricity markets are
designed. Formulation of unit commitment and economic dispatch as mathematical optimization. Modeling of thermal generators, renewable generators, energy storage, and other grid resources in power system optimization. Introduction of equilibrium in electricity markets. Introduction of ancillary service markets. Overview of current energy system research topics. Designed for masters and doctoral students, but is also open to undergraduates with the appropriate foundation classes.

**ELEN E4312x Analog electronic circuits**
3 pts. Lect: 3. Professor Dickson.
Prerequisite(s): ELEN E3331 and E3801.
Differential and multistage amplifiers; small-signal analysis; biasing techniques; frequency response; negative feedback; stability criteria; frequency compensation techniques. Analog layout techniques. An extensive design project is an integral part of the course.

**ELEN E4314y Communication circuits**
3 pts. Lect: 3. Professor Tsividis.
Prerequisite(s): ELEN E4312. Principles of electronic circuits used in the generation, transmission, and reception of signal waveforms, as used in analog and digital communication systems. Nonlinearity and distortion; power amplifiers; tuned amplifiers; oscillators; multipliers and mixers; modulators and demodulators; phase-locked loops. An extensive design project is an integral part of the course.

**EECS E4321x Digital VLSI circuits**
3 pts. Lect: 3. Professor Shepard.

**EECS E4340x Computer hardware design**
Prerequisite(s): ELEN E3331 and CSEE W3827. Practical aspects of computer hardware design through the implementation, simulation, and prototyping of a PDP-8 processor. High-level and assembly languages, I/O, interrupts, datapath and control design, pipelining, busses, memory architecture. Programmable logic and hardware prototyping with FPGAs. Fundamentals of VHDL for register-transfer level design. Testing and validation of hardware. Hands-on use of industry CAD tools for simulation and synthesis.

**ELEN E4611x or y Power electronics**
3 pts. Lect: 3. Professor Preindl.
Prerequisite(s): ELEN E3801 and E3331.
Introduction to power electronics; power semiconductor devices: power diodes, thyristors, commutation techniques, power transistors, power MOSFETs, Triac, IGBTs, etc., and switch selection; nonsinusoidal power definitions and computations, modeling, and simulation; half-wave rectifiers; single-phase, full-wave rectifiers; three-phase rectifiers; AC voltage controllers; DC/DC buck, boost, and buck-boost converters; discontinuous conduction mode of operation; DC power supplies: flyback, forward converter; DC/AC inverters, PWM techniques; three-phase inverters.

**ELEN E4411x Fundamentals of photonics**
3 pts. Lect: 3. Professor Lipson.

**ELEN E4488x Optical systems**
3 pts. Lect: 3. Professor Hendon.
Prerequisite(s): ELEN E3401 or equivalent. Introduction to optical systems based on physical design and engineering principles. Fundamental geometrical and wave optics with specific emphasis on developing analytical and numerical tools used in optical engineering design. Focus on applications that employ optical systems and networks, including examples in holographic imaging, tomography, Fourier imaging, confocal microscopy, optical signal processing, fiber optic communication systems, optical interconnects and networks.

**ELEN E4511x or y Power systems analysis and control**
3 pts. Lect: 3.
Prerequisite(s): ELEN E3201 and E3401, or equivalents, or instructor’s permission. Modeling of power networks, steady-state and transient behaviors, control and optimization, electricity market, and smart grid.

**EEME E460y Digital control systems**
3 pts. Lect: 3. Professor Longman.

**EEOR E4650y or y Convex optimization for electrical engineering**
3 pts. Lect: 3.
Prerequisite(s): ELEN E3801 or instructor’s permission. Theory of convex optimization; numerical algorithms; applications in circuits, communications, control, signal processing and power systems.

**ELEN E4702x or y Digital communications**
3 pts. Lect: 3. Professor Raghavan.
Prerequisite(s): ELEN E3701 or equivalent. Digital communications for both point-to-point and switched applications is further developed. Optimum receiver structures and transmitter signal shaping for both binary and M-ary signal transmission. An introduction to block codes and convolutional codes, with application to space communications.

**ELEN E4703y Wireless communications**
3 pts. Lect: 3. Professor Samardzic.
Prerequisite(s): ELEN E3701 or equivalent. Wireless communication systems. System design fundamentals. Trunking theory. Mobile radio propagation. Reflection of radio waves. Fading and multipath. Modulation techniques; signal space; probability of error, spread spectrum. Diversity. Multiple access.

**ELEN E4720x or y Machine learning for signals, information, and data**
3 pts. Lect: 3. Professor Paisley.
Prerequisite(s): Basic linear algebra and calculus. Intro-level courses in probability and statistics. Programming. Introduction to supervised and unsupervised techniques for machine learning. Probabilistic and non-probabilistic approaches. Focus on classification and regression models, clustering methods, matrix factorization and sequential models. Linear and logistic regression, support vector machines, boosting, K-means clustering, mixture models, expectation-maximization algorithm, and hidden Markov models. Algorithmic techniques for optimization, such as gradient and coordinate descent methods.

**BME E4740y Bioinstrumentation**
Prerequisite(s): COMS W1005, ELEN E1201. Hands-on experience designing, building, and testing the various components of a benchtop cardiac pacemaker. Design instrumentation to measure biomedical signals as well as to actuate living tissues. Transducers, signal conditioning electronics, data acquisition boards, the Arduino microprocessor, and data acquisition and processing using MATLAB will be covered. Various devices will be discussed throughout the course, with laboratory work focusing on building an emulated version of a cardiac pacemaker. Lab required.

**EECS E4750y or y Heterogeneous computing for signal and data processing**
3 pts. Lect: 2. Professor Mariantetti.
Prerequisite(s): ELEN E3801 and COMS W3134 or similar, recommended. Methods for deploying signal and data processing algorithms on contemporary general purpose graphics processing units (GPGPUs) and heterogeneous computing infrastructures. Using programming languages such as OpenCL and CUDA for computational speedup in audio, image, and video processing and computational data analysis. Significant design project.
ECECS E4764 Internet of things—intelligent and connected systems
3 pts. Lect 3. Professor Jiang.
Prerequisite(s): Knowledge of programming or instructor's permission. Recommended: ELEN E4703, CSEE W4119, CSEE W4840, or related courses. Cyber-physical systems and Internet of Things. Various sensors and actuators, communication with devices through serial protocols and buses, embedded hardware, wired and wireless networks, embedded platforms such as Arduino and smartphones, web services on end devices and in the cloud, visualization and analytics on sensor data, end-to-end IoT applications. Group projects to create working CPS/IoT system.

ECECS E4766 Internet of things—engineering innovations and commercialization
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): Basic programming and instructor's permission. Deep dive into a couple of selected topics/use-cases from the area of Internet of Things. Coverage of the topic from device to the cloud, with focus on practical aspects. Innovative product definition, product development, marketing, commercialization, and monetization. Cross-disciplinary coverage: EE, MechE, CS, Bioengineering, marketing, business, design. Building products and startups in the IoT domain. Collaboration between the Engineering School, Business School, industry experts, and engagement in IoT activities in NYC. Collaborative project by groups of students from different disciplines. This course shares lectures with E6766, but the expected project complexity is lower.

ELEN E4810x Digital signal processing
3 pts. Lect: 3. Professor Wright.
Prerequisite(s): ELEN E3801. Digital filtering in time and frequency domain, including properties of discrete-time signals and systems, sampling theory, transform analysis, system structures, IIR and FIR filter design techniques, the discrete Fourier transform, fast Fourier transforms.

ELEN E4815y Random signals and noise
3 pts. Lect: 3. Professor Kolet.
Prerequisite(s): IOR E3658 or equivalent. Characterization of stochastic processes as models of signals and noise; stationarity, ergodicity, correlation functions, and power spectra. Gaussian processes as models of noise in linear and nonlinear systems; linear and nonlinear transformations of random processes; orthogonal series representations. Applications to circuits and devices, to communication, control, filtering, and prediction.

CSEE W4823x or y Advanced logic design
3 pts. Lect: 3.
Prerequisite(s): CSEE W3827 or equivalent. An introduction to modern digital system design. Advanced topics in digital logic: controller synthesis (Mealy and Moore machines); adders and multipliers; structured logic blocks (PLDs, PALs, ROMs); iterative circuits. Modern design methodology; register transfer level modeling (RTL); algorithmic state machines (ASMs); introduction to hardware description languages (VHDL or Verilog); system-level modeling and simulation; design examples. Prediction.

CSEE W4824x or y Computer architecture
3 pts. Lect: 3. Professor Sethumadhavan.

ELEN E4830y Digital image processing
3 pts. Lect: 3. Professor Hendon.
Introduction to the mathematical tools and algorithmic implementation for representation and processing of digital pictures, videos, and visual sensory data. Image representation, filtering, transform, quality enhancement, restoration, feature extraction, object segmentation, motion analysis, classification, and coding for data compression. A series of programming assignments reinforces material from the lectures.

ELEN E4835y Introduction to adaptive signal representations
3 pts. Lect: 2. Professor Wright.
Prerequisite(s): Linear algebra (APMA E3101, MATH UN2010, or equivalent), probability (IEOR E3658 or equivalent), and signals and systems (ELEN E3801), or instructor's permission. Introduces numerical tools for adaptive processing of signals. Signal representations, sparsity in overcomplete bases. Techniques for sparse recovery, applications to inpainting and denoising. Adaptive representations: principal component analysis, clustering and vector quantization, dictionary learning. Source separation: independent component analysis and matrix factorizations. Signal classification: support vector machines and boosting, learning with invariances. Hashing and signal retrieval. Case studies from image processing, audio, multimedia.

CSEE W4840y Embedded systems
Prerequisite(s): CSEE W4823 or equivalent. Embedded system design and implementation combining hardware and software. I/O, interfacing, and peripherals. Weekly laboratory sessions and term project on design of a microprocessor-based embedded system including at least one custom peripheral. Knowledge of C programming and digital logic required.

CSEE E4868x or y System-on-chip platforms
3 pts. Lect: 3. Professor Carloni.
Prerequisite(s): COMS W3157 and CSEE W3827 Design and programming of System-on-Chip (SoC) platforms. Topics include overview of technology and economic trends, methodologies and supporting CAD tools for system-level design; models of computation, the SystemC language, transaction-level modeling, hardware-software partitioning, high-level synthesis, system programming, on-chip communication, memory organization, power management and optimization, integration of programmable processor cores and specialized accelerators. Case studies of modern SoC platforms for various classes of applications.

ELEN E4900-4909x or y Topics in electrical and computer engineering
Prerequisite(s): Instructor's permission. Selected topics in electrical and computer engineering. Content varies from year to year, and different topics rotate through the course numbers 4900 to 4909.

ELEN E4940x or y Principles of device microfabrication
3 pts. Lect: 3. Professor Trevino.
Science and technology of conventional and advanced microfabrication techniques for electronics, integrated and discrete components. Topics include diffusion; ion implantation, thin-film growth including oxides and metals, molecular beam and liquid-phase epitaxy; optical and advanced lithography; and plasma and wet etching.

ELEN E4998x or y Intermediate projects in electrical engineering
1–4 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Substantial independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

ELEN E6001x-E6002y Advanced projects in electrical engineering
1–4 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. May be repeated for up to 6 points of credit. Graduate-level projects in various areas of electrical engineering and computer science. In consultation with an instructor, each student designs their project depending on the student's previous training and experience. Students should consult with a professor in their area for detailed arrangements no later than the last day of registration.

ELEN E6003x and y Master's thesis
3 pts. Members of the faculty.
Prerequisite(s): A minimum of 3 points of credit in ELEN E601 or E6002 advanced projects with the same instructor, instructor's permission, and completion of at least 12 points of credit in MS program with GPA of at least 3.5. Research in area of Electrical Engineering culminating in a verbal presentation and a written thesis document approved by thesis instructor. Must obtain permission from thesis instructor to enroll. Thesis projects span at least two terms: ELEN E6001 or E6002 Advanced Project followed by E6003 Master's Thesis with same instructor. Students must use department recommended format for thesis writing. Counts towards total amount of research credit in M.S. program.
ELEN E6010y Systems biology: design concepts for biological circuits
4.5 pts. Lect: 3. Professor Jelenkovic.

ELEN E6020y Methods of computational neuroscience
4.5 pts. Lect: 3.
Prerequisite(s): BMEB W4020 or instructor’s permission. Formal methods in computational neuroscience including methods of signal processing, communications theory, information theory, systems and control, system identification and machine learning. Molecular models of transduction pathways. Robust adaptation and integral feedback. Stimulus representation and groups. Stochastic and dynamical systems models of spike generation. Neural diversity and ensemble encoding. Time encoding machines and neural codes. Stimulus recovery with time decoding machines. MIMO models of neural computation. Dynaptic plasticity and learning algorithms. Major project(s) in MATLAB.

BMEE E6030x Neural modeling and neuroengineering
3 pts. Lect: 3. Professor Saad.
Prerequisite(s): ELEN E3801 and either APMA E2101 or E3101, or equivalent, or instructor’s permission. Engineering perspective on the study of multiple levels of brain organization, from single neurons to cortical modules and systems. Mathematical models of spiking neurons, neural dynamics, neural coding, and biologically based computational learning. Architectures and learning principles underlying both artificial and biological neural networks. Computational models of cortical processing, with an emphasis on the visual system. Applications of principles in neuroengineering; neural prostheses, neuromorphic systems and biomimetics. Course will include a computer simulation laboratory.

ECBM E6040y Neural networks and deep learning research.
3 pts. Lect: 3. Professor Lazar.
Prerequisite(s): ECBM E4040 or the equivalent. Regularized autoencoders, sparse coding and predictive sparse decomposition, denoising autoencoders, representation learning, manifold perspective on representation learning, structured probabilistic models for deep learning, Monte Carlo methods, training and evaluating models with intractable partition functions, restricted Boltzmann machines, approximate inference, deep belief networks, deep learning in speech, and object recognition.

ELEN E6090–6099x or y Topics in computational neuroscience and neuroengineering
Prerequisite(s): Instructor’s permission. Selected advanced topics in computational neuroscience and neuroengineering. Content varies from year to year, and different topics rotate through the course numbers 6090 to 6099.

CSEE E6180x or y Modeling and performance evaluation
Prerequisite(s): COMS W4118 and STAT GU4001 or instructor’s permission. Introduction to queuing analysis and simulation techniques. Evaluation of time-sharing and multiprocessor systems. Topics include priority queuing, buffer storage, and disk access, interference and bus contention problems, and modeling of program behaviors.

ELEN E6201x Linear system theory

ELEN E6302x or y MOS transistors
3 pts. Lect: 2. Professor Tsividis.
Prerequisite(s): ELEN E3106 or equivalent. Operation and modeling of MOS transistors. MOS two- and three-terminal structures. The MOS transistor as a four-terminal device; general charge-sheet modeling; strong, moderate, and weak inversion models; short- and narrow-channel effects; ion-implanted devices; scaling considerations in VLSI; charge modeling; large-signal transient and small-signal modeling for quasistatic and nonquasistatic operation.

ELEN E6312y Advanced analog integrated circuits
Prerequisite(s): ELEN E4312. Integrated circuit device characteristics and models; temperature- and supply-independent biasing; IC operational amplifier analysis and design and their applications; feedback amplifiers, stability and frequency compensation techniques; noise in circuits and low-noise design; mismatch in circuits and low-offset design. Computer-aided analysis techniques are used in homework or a design project.

ELEN E6314x Advanced communication circuits
3 pts. Lect: 2.
Prerequisite(s): ELEN E4314 and E6312. Overview of communication systems, modulation and detection schemes. Receiver and transmitter architectures. Noise, sensitivity, and dynamic range. Nonlinearity and distortion. Low-noise RF amplifiers, mixers, and oscillators. Phase-locked loops and frequency synthesizers. Typical applications discussed include wireless RF transceivers or data links. Computer-aided analysis techniques are used in homework(s) or a design project.

ELEN E6316y Analog-digital interfaces in VLSI
3 pts. Lect: 3. Professor Dickson.
Prerequisite(s): ELEN E4312 or equivalent. Analog-to-digital and digital-to-analog conversion techniques for very large scale integrated circuits and systems. Precision sampling; quantization; A/D and D/A converter architectures and metrics; Nyquist architectures; oversampling architectures; correction techniques; system considerations. A design project is an integral part of this course.

ELEN E6318x or y Microwave circuit design
3 pts. Lect: 3. Professor Boeyens.
Prerequisite(s): ELEN E3331 and E3401, or equivalents. Introduction to microwave engineering and microwave circuit design. Review of transmission lines. Smith chart, S-parameters, microwave impedance matching, transformation and power combining networks, active and passive microwave devices, S-parameter-based design of RF and microwave amplifiers. A microwave circuit design project (using microwave CAD) is an integral part of the course.

ELEN E6320x or y Millimeter-wave IC design
3 pts. Lect: 3. Professor Krishnaswamy.
Prerequisite(s): ELEN E3401 or equivalent, ELEN E4314 and E6312. Principles behind the implementation of millimeter-wave (30GHz-300GHz) wireless circuits and systems in silicon-based technologies. Silicon-based active and passive devices for millimeter-wave operation, millimeter-wave low-noise amplifiers, power amplifiers, oscillators and VCOs, oscillator phase noise theory, mixers and frequency dividers for PLLs. A design project is an integral part of the course.

EECS E6321y Advanced digital electronic circuits
3 pts. Lect: 2. Professor Seok.
Prerequisite(s): EECS E4321. Advanced topics in the design of digital integrated circuits. Clocked and non-clocked combinational logic styles. Timing circuits: latches and flip-flops, phase-locked loops, delay-locked loops. SRAM and DRAM memory circuits. Modeling and analysis of on-chip interconnect. Power distribution and power-supply noise. Clocking, timing, and synchronization issues. Circuits for chip-to-chip electrical communication. Advanced technology issues that affect circuit design. The class may include a team circuit design project.

EECS E6322x VLSI Hardware architecture for signal processing and machine learning
3 pts. Lect: 3. Professor Seok.
Prerequisite(s): CSEE W3827 and ELEN E3801. Recommended: ELEN E4810. Design of digital VLSI hardware for various digital signal processing and machine learning algorithms. Data flow graphs, iteration bounds, pipelining, parallel architectures, retiming, unfolding/folding, systolic architectures, bit-level arithmetic, numerical
and algorithmic strength reductions, CORDIC, distributed arithmetic, FFT, neural network hardware, vector processors, subwordparallel architecture, and SIMD. May include a team circuit design project.

**ELEN E6324x or y Principles of RF and microwave measurement**
3 pts. Lect: 3. Professor Shahramian.
Prerequisite(s): ELEN E4314 or equivalent, or instructor's permission. Principles behind, and techniques related to, RF and microwave simulation and measurements. S parameters; simulations and measurements for small-signal and large signal / nonlinear circuits in the time and frequency domains; noise.

**ELEN E633ty Principles of semiconductor physics, I**
Prerequisite(s): ELEN E4301. Designed for students interested in research in semiconductor materials and devices. Topics include energy bands: nearly free electron and tight-binding approximations, the k·p method, quantitative calculation of band structures and their applications to quantum structure transistors, photodetectors, and lasers; semiconductor statistics, Boltzmann transport equation, scattering processes, quantum effect in transport phenomena, properties of heterostructures. Quantum mechanical treatment throughout.

**ELEN E6332y Principles of semiconductor physics, II**
3 pts. Lect: 2.
Prerequisite(s): ELEN E3106 or ELEN E6331. Optical properties including absorption and emission of radiation, electron-phonon interactions, radiative and phonon-mediated processes, excitons, plasmons, polaritons, carrier recombinaction and generation, and related optical devices, tunneling phenomena, superconductivity. Quantum mechanical treatment throughout, heavy use of perturbation theory.

**ELEN E6333y Semiconductor device physics**
3 pts. Lect: 2.
Prerequisite(s): ELEN E3106 or ELEN E4301 or equivalent. Physics and properties of semiconductors. Transport and recombination of excess carriers. Schottky, P-N, MOS, and heterojunction diodes. Field effect and bipolar junction transistors. Dielectric and optical properties. Optical devices including semiconductor lamps, lasers, and detectors.

**ELEN E6350y VLSI design laboratory**
3 pts. Lab: 3.
Prerequisite(s): ELEN E4321 and E4312, or instructor's permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E4350, but the complexity requirements of integrated circuits are higher.

**ELEN E6412y Lightwave devices**
Prerequisite(s): ELEN E4411. Electro-optics: principles; electro-optics of liquid crystals and photo-refractive materials. Nonlinear optics: second-order nonlinear optics; third-order nonlinear optics; pulse propagation and solitons. Acousto-optics: interaction of light and sound; acousto-optic devices. Photonic switching and computing: photonics switches; all-optical switches; bistable optical devices. Introduction to fiber-optic communications: components of the fiber-optic link; modulation, multiplexing and coupling; system performance; receiver sensitivity; coherent optical communications.

**ELEN E6413y Lightwave systems**
3 pts. Lect: 2. Professor Feuer.

**ELEN E6414y Photonic integrated circuits**
3 pts. Lect: 3.
Photonic integrated circuits are important subsystem components for telecommunications, optically controlled radar, optical signal processing, and photonic local area networks. An introduction to the devices and the design of these circuits. Principle and modeling of dielectric waveguides (including silica on silicon and InP based materials), waveguide devices (simple and star couplers), and surface diffractive elements. Discussion of numerical techniques for modeling circuits, including beam propagation and finite difference codes, and design of other devices: optical isolators, demultiplexers.

**ELEN E6430x or y Applied quantum optics**
3 pts. Lect: 2.
Prerequisite(s): Background in electromagnetism (ELEN E3401, E4401, E4411, or PHYS GR6092) and quantum mechanics (APPH E3100, E4100, or PHYS GU4022). An introduction to fundamental concepts of quantum optics and quantum electrodynamics with an emphasis on applications in nanophotonic devices. The quantization of the electromagnetic field; coherent and squeezed states of light; interaction between light and electrons in the language of quantum electrodynamics (QED); optical resonators and cavity QED; low-threshold lasers; and entangled states of light.

**ELEN E6488y Optical interconnects and interconnection networks**
3 pts. Lect: 2. Professor Bergman.
Prerequisite(s): ELEN E4411 or E4488 or an equivalent photonics course. Introduction to optical interconnects and interconnection networks for digital systems. Fundamental optical interconnects technologies, optical interconnection network design, characterization, and performance evaluation. Enabling photonic technologies including free-space structures, hybrid and monolithic integration platforms for photonic on-chip, chip-to-chip, backend, and node-to-node interconnects, as well as photonic networks on-chip.

**EEME E6601x Introduction to control theory**
3 pts. Lect: 3. Professor Longman.
Prerequisite(s): MATH UN2030. A graduate-level introduction to classical and modern feedback control that does not presume an undergraduate background in control. Scalar and matrix differential equation models, and solutions in terms of state transition matrices. Transfer functions and transfer function matrices, block diagram manipulations, closed-loop response. Proportional, rate, and integral controllers, and compensators. Design by root locus and frequency response. Controllability, observability. Luenberger observers, pole placement, and linear-quadratic cost controllers.

**EECS E6690-6699x or y Topics in data-driven analysis and computation**
4.5 pts. Lect: 3. Professor Barbasthen.
Prerequisite(s): the instructor's permission. Selected advanced topics in data-driven analysis and computation. Content varies from year to year, and different topics rotate through the course numbers 6690 to 6699.

**ELEN E6711x Stochastic models in information systems**
3 pts. Lect: 2.
Prerequisite(s): ELEN E4815, or equivalent, or instructor's permission. Representation of signals and networks on-chip. May include a team circuit design project.

**EEOR E6616x or y Convex optimization**

**EECS E6690-6699x or y Topics in data-driven analysis and computation**
Prerequisite(s): the instructor's permission. Selected advanced topics in data-driven analysis and computation. Content varies from year to year, and different topics rotate through the course numbers 6690 to 6699.

**ELEN E6711x Stochastic models in information systems**
4.5 pts. Lect: 3. Professor Barbasthen.
Prerequisite(s): EEOR E6613 and EOR E6450. Foundations: probability review, Poisson processes, discrete-time Markov models, continuous-time Markov models, stationarity, and ergodicity. The course presents a sample-path (time domain) treatment of stochastic models arising in information systems, including at least one of the following areas: communications networks (queueing systems), biological networks (hidden Markov models), Bayesian restoration of images (Gibbs fields), and electric networks (random walks).

**ELEN E6712x Communication theory**
3 pts. Lect: 3.
Prerequisite(s): ELEN E4815, or equivalent, or instructor's permission. Representation of bandlimited signals and systems. Coherent and incoherent communications over Gaussian channels. Basic digital modulation schemes. Intersymbol inference channels. Fading multipath channels. Carrier and clock synchronization.

**ELEN E6713y Topics in communications**
3 pts. Lect: 3.
Prerequisite(s): ELEN E6712 or E4702 or E4703 or equivalent, or instructor’s permission. Advanced topics in communications, such as turbo codes, LDPC codes, multilayer communications, network coding, cross-layer optimization, cognitive radio. Content may vary from year to year to reflect the latest development in the field.

ELEN E6717x Information theory

ELEN E6718y Error correcting codes: classical and modern
3 pts. Lect: 2. Professor Ashikhmin.
Prerequisite(s): IEOR E3658. Main concepts of error control codes. Linear block codes. Elements of algebra: Galois fields. BCH and Reed Solomon codes. Convolutional Codes. Modern, capacity-achieving codes: Low Density Parity Check codes, TURBO codes, and Polar codes. EXIT Charts analysis.

EECS E6720 Bayesian models for machine learning
3 pts. Lect: 3. Professor Paisley.
Prerequisite(s): Basic calculus, linear algebra, probability, and programming. Basic statistics and machine learning strongly recommended. Bayesian approaches to machine learning. Topics include mixed-membership models, latent factor models, Bayesian nonparametric methods, probit classification, hidden Markov models, Gaussian mixture models, model learning with mean-field variational inference, scalable inference for Big Data. Applications include image processing, topic modeling, collaborative filtering, and recommendation systems.

ELEN E6761y Speech and audio processing I
3 pts. Lect: 3. Professor Ghaderi.
Prerequisite(s): IEOR E3658 or equivalent, or instructor’s permission. Recommended: CSEE W4119. Analytical approach to the design of (data) communication networks. Necessary tools for performance analysis and design of network protocols and algorithms. Practical engineering applications in layered internet protocols in Data link layer, Network layer, and Transport layer. Review of relevant aspects of stochastic processes, control, and optimization.

EECS E6765 Internet of things—systems and physical data analytics
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): Knowledge of programming; ELEN E4703 or related; or CSEE W4119; or instructor’s permission. Internet of Things from the point of view of data. Methods for data analytics to understand trade-offs and partitioning between cloud-based data-analytics and physical-device data analytics. Two-way interaction between data and physical devices to support a truly ubiquitous, networked, and autonomous cyber-physical ecosystem. System-focused design of architectures, algorithms, networks, protocols, communications, power, security, and standards. Focus on a significant design project.

ELEN E6767x or y Internet economics, engineering, and the implications for society
3 pts. Lect: 2. Professor Mitra.
Prerequisite(s): CSEE W4119 or ELEN E6761 recommended, and ability to comprehend and track development of sophisticated models. Mathematical models, analyses of economics and networking interdependencies in the internet. Topics include microeconomics of pricing and regulations in communications industry, game theory in revenue allocations, ISP settlements, network externalities, two-sided markets. Economic principles in networking and network design, decentralized vs. centralized resource allocation, “price of anarchy,” congestion control. Case studies of topical internet issues. Societal and industry implications of internet evolution.

ELEN E6770–6779x or y Topics in networking
3 pts. Lect: 2. Members of the faculty. Further study of areas such as communication protocols and architectures, flow and congestion control in data networks, performance evaluation in integrated networks. Content varies from year to year, and different topics rotate through the course numbers 6770 to 6779.

ELEN E6820y Speech and audio processing and recognition
3 pts. Lect: 2. Professor Mesgarani.
Prerequisite(s): ELEN E4810 or instructor’s permission. Fundamentals of digital speech processing and audio signals. Acoustic and perceptual basics of audio. Short-time Fourier analysis. Analysis and filter bank models. Speech and audio coding, compression, and reconstruction. Acoustic feature extraction and classification. Recognition techniques for speech and other sounds, including hidden Markov models.

CSEE E6824y Parallel computer architecture
3 pts. Lect: 2.
Prerequisite(s): CSEE W4824. Parallel computer principles, machine organization and design of parallel systems including parallelism detection methods, synchronization, data coherence and interconnection networks. Performance analysis and special purpose parallel machines.

CSEE E6847y Distributed embedded systems
3 pts. Lect: 2.
Prerequisite(s): Any COMS W411X, CSEE W48XX, or ELEN E43XX course, or instructor’s permission. An interdisciplinary graduate-level seminar on the design of distributed embedded systems. System robustness in the presence of highly variable communication delays and heterogeneous component behaviors. The study of the enabling technologies (VLSI circuits, communication protocols, embedded processors, RTOSSs), models of computation, and design methods. The analysis of modern domain-specific applications including on-chip micro-networks, multiprocessor systems, fault-tolerant architectures, and robust deployment of embedded software. Research challenges such as design complexity, reliability, scalability, safety, and security. The course requires substantial reading, class participation and a research project.

ELEN E6860y Advanced digital signal processing
3 pts. Lect: 2. Professor Nguyen.
Prerequisite(s): ELEN E4810. This course is designed as an extension to ELEN E4810, with emphasis on emerging techniques in the area of digital signal processing. Topics include multirate signal processing, multidimensional signal processing, short-time Fourier transform, signal expansion in discrete and continuous time, filter banks, multisresolution analysis, wavelets, and their applications to image compression and understanding. Other topics may be included to reflect developments in the field.

CSEE E6861y Computer-aided design of digital systems
Prerequisite(s): (i) one semester of advanced digital logic (CSEE W4823 or equivalent, or instructor’s permission); and (ii) a basic course in data structures and algorithms (COMS W3133, W3134, W3137, W3139 or W3157, or equivalent), and familiarity with programming. Introduction to modern digital CAD synthesis and optimization techniques. Topics include modern digital system design (high-level synthesis, register-transfer level modeling, algorithmic state machines, optimal scheduling algorithms, resource allocation and binding, retiming), controller synthesis and optimization, exact and heuristic two-level logic minimization, advanced multi-level logic optimization, optimal technology mapping to library cells (for delay, power and area minimization), advanced data structures (binary decision diagrams), SAT solvers and their applications, static timing analysis, and introduction to testability. Includes hands-on small design projects using and creating CAD tools.

CSEE E6863 Formal verification of hardware and software systems
3 pts. Lect: 2. Professor Theobald and Ivancic.
Prerequisite(s): COMS W3134, W3136, or W3137 and COMS W3261. Introduction to the theory and practice of formal methods for the design and analysis of correct (i.e., bug-free) concurrent and embedded hardware/software systems. Topics include temporal logics; model checking; deadlock and liveness issues; fairness; satisfiability (SAT) checkers; binary decision diagrams (BDDs); abstraction techniques; introduction to commercial formal verification tools. Industrial state-of-the-art, case studies and experiences: software analysis (C/C++/Java), hardware verification (RTL).

CSEE E6868x or y Embedded scalable platforms
3 pts. Lect: 2. Professor Carloni.
Prerequisite(s): CSEE W4868 or instructor’s permission.
permission. Inter-disciplinary graduate-level seminar on design and programming of embedded scalable platforms. Content varies between offerings to cover timely relevant issues and latest advances in system-on-chip design, embedded software programming and electronic design automation. Requires substantial reading of research papers, class participation, and semester-long project.

**ECECS 6870x or y Speech recognition**
3 pts. Lect: 2.
Prerequisite(s): Basic probability and statistics. Theory and practice of contemporary automatic speech recognition. Gaussian mixture distributions, hidden Markov models, pronunciation modeling, decision trees, finite-state transducers, and language modeling. Selected advanced topics will be covered in more depth.

**ECECS 6873x or y Detection and estimation theory**
3 pts. Lect: 2.
Prerequisite(s): ELE E4815. Introduction to the fundamental principles of statistical signal processing related to detection and estimation. Hypothesis testing, signal detection, parameter estimation, signal estimation, and selected advanced topics. Suitable for students doing research in communications, control, signal processing, and related areas.

**ECECS 6876x or y Sparse and low-dimensional models for high-dimensional data**
3 pts. Lect: 3. Professor Wright.
Prerequisite(s): ELE E4815 or equivalent and linear algebra. Recommended: ELE E4810 or equivalent. Overview of theory, computation and applications for sparse and low-dimensional data modeling. Recoverability of sparse and low-rank models. Optimization methods for low-dim data modeling. Applications to imaging, neuroscience, communications, web data.

**ECECS 6880-6889x or y Topics in signal processing**
Prerequisite(s): ELE E4810. Advanced topics in signal processing, such as multidimensional signal processing, image feature extraction, image/video editing and indexing, advanced digital filter design, multirate signal processing, adaptive signal processing, and wave-form coding of signals. Content varies from year to year, and different topics rotate through the course numbers 6880 to 6889.

**ECECS 6890-6899x or y Topics in information processing**
Advanced topics spanning electrical engineering and computer science such as speech processing and recognition, image and multimedia content analysis, and other areas drawing on signal processing, information theory, machine learning, pattern recognition, and related topics. Content varies from year to year, and different topics rotate through the course numbers 6890 to 6899.

**ECECS 6900-6909x or y Topics in electrical and computer engineering**
Prerequisite(s): Instructor’s permission. Selected topics in electrical and computer engineering. Content varies from year to year, and different topics rotate through the course numbers 6900 to 6909.

**ECECS 6910-6919x or y Topics in technical writing and presentation for electrical engineers**
1 pt. Professor Kayfetz.
Open to M.S. and Ph.D. students in EE/CE with instructor’s permission. Topics to help EE/CE graduate students’ communication skills. Emphasis on writing clear, concise proposals, journal articles, conference papers, and theses, and on preparing clear technical presentations. Different topics rotate through the course numbers 6910 to 6919. May be repeated for credit. Credit may not be used to satisfy degree requirements.

**ECECS 6945x or y Device nanofabrication**
3 pts. Lect: 3.
Prerequisite(s): ELE E3060 and E3401, or equivalents. Recommended: ELE E4944. This course provides an understanding of the methods used for structuring matter on the nanometer length: thin-film technology; lithographic patterning and technologies including photon, electron, ion and atom, scanning probe, soft lithography, and nanoimprinting; pattern transfer; self-assembly; process integration; and applications.

**ECECS 6950x Wireless and mobile networking, I**
Corequisite(s): ELE E6761 or instructor’s permission. Overview of mobile and wireless networking. Fundamental concepts in mobile wireless systems: propagation and fading, cellular systems, channel assignment, power control, handoff. Examples of second-generation circuits-switched systems and standards. Quantitative homework assignments may require use of a mathematical software package.

**ECECS 6999x, y, or s Fieldwork**
0.5–1.5 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used for degree credit. Only for electrical engineering and computer engineering graduate students who include relevant off-campus work experience as part of their approved program of study. Final report required. May not be taken for pass/fail credit or audited.

**ECECS 8600y Advanced topics in control theory**
3 pts. Lect: 3. Members of the faculty.
See entry under “Courses in Mechanical Engineering” for description.

**ECECS 9001x and y–E9012 Doctoral research instruction**
0–6 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. Points of credit to be approved by the department. Requires submission of an outline of the proposed research for approval by the faculty member who is to supervise the work of the student. The research facilities of the department are available to qualified students interested in advanced study.

**ECECS 9011x and y Doctoral dissertation**
0 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in electrical engineering must register for 12 points of doctoral research instruction. Registration in ECECS 9000 may not be used to satisfy the minimum residence requirement for the degree.

**ECECS 9000x, y and s Doctoral dissertation**
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the student’s coursework has been completed, and until the dissertation has been accepted.

**COURSES IN ELECTRICAL ENGINEERING OFFERED OCCASIONALLY**

**ECBM E3060x Introduction to genomic information science and technology**
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function, and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. This course shares lectures with ECBM E4060, but the work requirements differ somewhat.

**EEHS E3900y History of telecommunications:**
3 pts. Lect: 3.
Historical development of telecommunications from the telegraph to the internet. The internet at present. Included are the technologies of telephony, radio, and computer communications. The coverage includes both the technologies themselves and the historical events that shaped, and in turn were shaped by, the technologies. The historical development, both the general context and the particular events concerning communications, is presented...
chronologically. The social needs that elicted new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are explained as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking principles. There are no prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective. The course shares lectures with EEHS E4900, but the work requirements differ somewhat.

ELEN E3999x or y Electrical engineering design challenge
1 pt.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Short-term design project organized as a faculty-led team competition. Particular design targets are set that vary by semester. A set of hardware and software constraints is specified. The project takes places over an advertised subset of the semester, beginning around the third week.

BMEE E4030y Neural control engineering
3 pts. Lect: 3.
Prerequisite(s): ELEN E3801. Topics include basic cell biophysics, active conduction and the Hodgkin-Huxley model, simple neuron models, ion channel models and synaptic models, statistical models of spike generation, Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, sensorimotor integration and optimal state estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and somatosensory pathway, neural encoding model: spike triggered average (STA) and spike triggered covariance (STC) analysis, neuronal response to electrical micro-stimulation, DBS for Parkinson’s disease treatment, motor neural prostheses, and sensory neural prostheses.

ELEN E4215y Analog filter synthesis and design
3 pts. Lect: 3.
Prerequisite(s): ELEN E3201 and ELEN E3801, or equivalent. Approximation techniques for magnitude, phase, and delay specifications, transfer function realization sensitivity, passive LC filters, active RC filters, MOSFET-C filters, 6m-C filters, switched-capacitor filters, automatic tuning techniques for integrated filters. Filter noise. A design project is an integral part of the course.

ELEN E4430x or y Magnetic sensors and instruments for medical imaging
3 pts. Lect: 2.5, Lab: 0.5.
Prerequisite(s): ELEN E3106, ELEN E3401, or instructor’s permission. Physics of nuclear magnetic resonance (NMR) and superconducting quantum interference device (SQUID). Design and operation of superconducting DC magnet, RF receiver, Josephson junction, and integrated SQUID. Principles of biomedical sensing systems including Magnetic Resonance Imaging (MRI), SQUID magnetometer, and NMR spectroscopy. Medical image formation and processing.

ELEN E4350y VLSI design laboratory
3 pts. Lab: 3.
Prerequisite(s): EECS E4212 and ELEN E4212, or instructor’s permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E6350, but the complexity requirements of integrated circuits are lower.

BMEE E4400x Wavelet applications in biomedical image and signal processing
3 pts. Lect: 3.
Prerequisite(s): APMA E2101 or E3101 or equivalent. An introduction to methods of wavelet analysis and processing techniques for the quantification of biomedical images and signals. Topics include frames and overcomplete representations, multisresolution algorithms for denoising and image restoration, multiscale texture segmentation, and classification methods for computer-aided diagnosis.

ELEN E4401x Wave transmission and fiber optics
3 pts. Lect: 3.

ELEN E4420x Topics in electromagnetics
3 pts. Lect: 3.
Prerequisite(s): Undergraduate electromagnetic theory. Selected topics in the theory and practice of electromagnetics, varying from year to year. Topic for current term will be available in the department office one month before registration. This course may be taken more than once when topics are different. Possible topics: microwave theory and design (generalized waveguides, excitation and coupling of waveguides, junctions, microwave networks, periodic structures, optical fibers); antennas (filamentary antennas, arrays, aperture radiation, system properties, pattern synthesis); electrodynamics (special relativity, radiation by charged particles, relativistic beams, free electron lasers).

ELEN E4501x Electromagnetic devices and energy conversion
3 pts. Lect: 3. Professor Sen.
Prerequisite(s): ELEN E3401. Linear and nonlinear magnetic circuits. Electric and magnetic energy storage, loss, and transfer. Circuit behavior of energy storage and transfer devices. Field theory of moving bodies. Dynamical equations of an electromechanical system. Electromechanical and thermo-electric sensors and actuators. Rotating electric energy converters. Superconductivity and applications.

ELEN E4503x Sensors, actuators, and electromechanical systems
3 pts. Lect: 3.

ELEN E4510x or y Solar energy and smart grid power systems

ELEN E4896y Music signal processing
3 pts. Lect: 3.
Prerequisite(s): ELEN E3801, E4810, or the equivalent. An investigation of the applications of signal processing to music audio, spanning the synthesis of musical sounds (including frequency modulation [FM], additive sinusoidal synthesis, and linear predictive coding [LPC]), the modification of real and synthetic sounds (including reverberation and time/pitch scaling), and the analysis of music audio to extract musical information (including pitch tracking, chord transcription, and music matching). Emphasis on practical, hands-on experimentation, with a wide range of software implementations introduced and modified within the class.
ELEN E6080–6089x or y Topics in systems biology
Prerequisite(s): Instructor’s permission. Selected advanced topics in systems biology. Content varies from year to year, and different topics rotate through the course numbers 6080 to 6089.

ELEN E6151y Surface physics and analysis of electronic materials
3 pts. Lect: 2.
Prerequisite(s): Instructor’s permission. Basic physical principles of methods of surface analysis, surfaces of electronic materials including structure and optical properties (auger electron spectroscopy, X-ray photoemission, ultraviolet photoelectron spectroscopy, electron energy loss spectroscopy, inverse photoemission, photo stimulated desorption, and low energy electron diffraction), physical principles of each approach.

ELEN E6211x or y Circuit theory
3 pts. Lect: 3.

ELEN E6265y Computational methods of circuit analysis
3 pts. Lect: 3.
Prerequisite(s): ELEN E3331 and APMA E3101. Computational algorithms for DC, transient, and frequency analysis of linear and nonlinear circuits. Formulation of equations: state equations, hybrid equations, sparse tables. Solution techniques: iterative methods to solve nonlinear algebraic equations; piecewise linear methods; sparse matrix techniques; numerical integration of stiff, nonlinear differential equations, companion network models; waveform relaxation.

ELEN E6304x or y Topics in electronic circuits
3 pts. Lect: 3.
Prerequisite(s): Instructor’s permission. State-of-the-art techniques in integrated circuits. Topics may change from year to year.

EEME E6602y Modern control theory
3 pts. Lect: 3.
Prerequisite(s): EEME E6601 or E4601 or ELEN E6201, or instructor’s permission. Singular value decomposition. ARX model and state-space model system identification. Recursive least squares filters and Kalman filters. LQR, H, linear robust control, predictive control. Learning control, repetitive control, adaptive control. Liapunov and Popov stability. Nonlinear adaptive control, nonlinear robust control, sliding mode control.

EEME E6610x Optimal control theory
3 pts. Lect: 3.

ELEN E6762y Computer communication networks, II
3 pts. Lect: 2.
Prerequisite(s): ELEN E6761. Broadband ISDN, services and protocols; ATM. Traffic characterization and modeling: Markov-modulated Poisson and Fluid Flow processes; application to voice, video, and images. Traffic Management in ATM networks: access and admission control, flow control. ATM switch architectures; input/output queueing. Quality of service (QoS) concepts.

EECS E6766x Internet of things—engineering innovations and commercialization
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): Basic programming and instructor’s permission. Deep dive into a couple of selected topics/use-cases from the area of Internet of Things. Coverage of the topic from device to the cloud, with focus on practical aspects. Innovative product definition, product development, marketing, commercialization, and monetization. Cross-disciplinary coverage: EE, MechE, CS, Bioengineering, marketing, business, design. Building products and start-ups in the IoT domain. Collaboration between the Engineering School, Business School, industry experts, and engagement in IoT activities in NYC. Collaborative project by groups of students from different disciplines. This course shares lectures with E4766, but a more complex project is expected.

ELEN E6850x Visual information systems
3 pts. Lect: 2.
Prerequisite(s): ELEN E4830 or instructor’s permission. Introduction to critical image technologies in advanced visual information systems, such as content-based image databases, video servers, and desktop video editors. Intended for graduate students. Topics include visual data representation and compression, content-based visual indexing and retrieval, storage system design (data placement, scheduling, and admission control), compressed video editing, and synchronization issues of stored video/audio signals. Programming projects and final presentations are required.
ELEN E9403x or y Seminar in photonics
3 pts. Lect: 2.
Prerequisite(s): ELEN E4411. Open to doctoral candidates, and to qualified M.S. candidates with instructor’s permission. Recent experimental and theoretical developments in various areas of photonics research. Examples of topics that may be treated include squeezed-light generation, quantum optics, photon detection, nonlinear optical effects, and ultrafast optics.

ELEN E9404x or y Seminar in lightwave communications
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s approval. Recent theoretical and experimental developments in light wave communications research. Examples of topics that may be treated include information capacity of light wave channels, photonic switching, novel light wave network architectures, and optical neural networks.

ELEN E9501x or y Seminar in electrical power networks
3 pts. Lect: 2.
Prerequisite(s): Open to doctoral candidates, and to qualified M.S. candidates with the instructor’s permission. Recent developments in control & optimization for power systems, design of smart grid, and related topics.

EECS E9601x or y Seminar in data-driven analysis and computation
3 pts. Lect: 2.
Prerequisite(s): Open to doctoral candidates and qualified M.S. candidates with the instructor’s permission. Advanced topics and recent developments in mathematical techniques and computational tools for data science and engineering problems.

ELEN E9701x or y Seminar in information and communication theories
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s permission. Recent developments in telecommunication networks, information and communication theories, and related topics.

ELEN E9705x or y Seminar in cyber-physical systems
3 pts.
Open to doctoral candidates and to qualified M.S. candidates with instructor’s permission. Advanced topics in recent developments in research on cyber-physical systems (CPS) and related topics.

ELEN E9801x or y Seminar in signal processing
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s approval. Recent developments in theory and applications of signal processing, machine learning, content analysis, and related topics.
Industrial engineering is the branch of the engineering profession that is concerned with the design, analysis, and control of production and service systems. Originally, an industrial engineer worked in a manufacturing plant and was involved only with the operating efficiency of workers and machines. Today, industrial engineers are more broadly concerned with productivity and all of the technical problems of production management and control. They may be found in every kind of organization: manufacturing, distribution, transportation, mercantile, and service. Their responsibilities range from the design of unit operations to that of controlling complete production and service systems. Their jobs involve the integration of the physical, financial, economic, computer, and human components of such systems to attain specified goals. Industrial engineering includes activities such as production planning and control; quality control; inventory, equipment, warehouse, and materials management; plant layout; and workstation design.

Operations research is concerned with quantitative decision problems, generally involving the allocation and control of limited resources. Such problems arise, for example, in the operations of industrial firms, financial institutions, health care organizations, transportation systems, and government. The operations research analyst develops and uses mathematical and statistical models to help solve these decision problems. Like engineers, they are problem formulators and solvers. Their work requires the formation of a mathematical model of a system and the analysis and prediction of the consequences of alternate modes of operating the system. The analysis may involve mathematical optimization techniques, probabilistic and statistical methods, experiments, and computer simulations.

Management Science and Engineering (also known as Engineering Management Systems) is a multidisciplinary field integrating industrial engineering, operations research, contemporary technology, business, economics, and management. It provides a foundation for decision making and managing risks in complex systems.

Financial engineering is a multidisciplinary field integrating financial theory with economics, methods of engineering, tools of mathematics, and practice of programming. The field provides training in the application of engineering methodologies and quantitative methods to finance.

Business Analytics involves the use of data science tools for solving operational and marketing problems. Students learn to leverage advanced quantitative models, algorithms, and data for making actionable decisions to improve business operations.
Current Research Activities
In industrial engineering, research is conducted in the area of logistics, routing, scheduling, production and supply chain management, inventory control, revenue management, and quality control.

In operations research, new developments are being explored in mathematical programming, combinatorial optimization, stochastic modeling, computational and mathematical finance, queueing theory, reliability, simulation, and both deterministic and stochastic network flows.

In engineering and management systems, research is conducted in the areas of logistics, supply chain optimization, and revenue and risk management.

In financial engineering, research is being carried out in portfolio management; option pricing, including exotic and real options; computational finance, such as Monte Carlo simulation and numerical methods; as well as data mining and risk management.

Projects are sponsored and supported by leading private firms and government agencies. In addition, our students and faculty are involved in the work of four research and educational centers: the Center for Applied Probability (CAP), the Center for Financial Engineering (CFE), the Computational and Optimization Research Center (CORC), and the FDT Center for Intelligent Asset Management.

The Center for Applied Probability (CAP) is a cooperative center involving the School of Engineering and Applied Science, several departments in the Graduate School of Arts and Sciences, and Columbia Business School. Its interests are in four applied areas: mathematical and computational finance, stochastic networks, logistics and distribution, and population dynamics.

The Center for Financial Engineering (CFE) at Columbia University encourages interdisciplinary research in financial engineering and mathematical modeling in finance and promoting collaboration between Columbia faculty and financial institutions, through the organization of research seminars, workshops, and the dissemination of research done by members of the Center.

The Computational Optimization Research Center (CORC) at Columbia University is an interdisciplinary group of researchers from a variety of departments on the Columbia campus. Its permanent members are Professors Daniel Bienstock, Don Goldfarb, Garud Iyengar, Jay Sethuraman, and Cliff Stein, from the Industrial Engineering and Operations Research Department, and Professor David Bayer, from the Department of Mathematics at Barnard College. Researchers at CORC specialize in the design and implementation of state-of-the-art algorithms for the solution of large-scale optimization problems arising from a wide variety of industrial and commercial applications.

The FDT Center for Intelligent Asset Management is led by Professor Xunyu Zhou at Columbia University. The Center will focus on the exploration of theoretical underpinnings and modeling strategies for financial portfolio management through the introduction of big data analytical techniques. The Center’s research will combine modern portfolio theory, behavioral finance, machine learning, and data science to study core problems including optimal asset allocation and risk management; and the research of the Center sits at the crossroads of financial engineering, computer science, statistics, and finance, aiming at providing innovative and intelligent investment solutions.

BACHELOR OF SCIENCE PROGRAMS

Industrial Engineering
The undergraduate program is designed to develop the technical skills and intellectual discipline needed by our graduates to become leaders in industrial engineering and related professions. The program is distinctive in its emphasis on quantitative, economic, computer-aided approaches to production and service management problems. It is focused on providing an experimental and mathematical problem-formulating and problem-solving framework for industrial engineering work. The curriculum provides a broad foundation in the current ideas, models, and methods of industrial engineering. It also includes a substantial component in the humanities and social sciences to help students understand the societal implications of their work.

The industrial engineering program objectives are:

1. To provide students with the requisite analytical and computational skills to assess practical situations and academic problems, formulate models of the problems represented or embedded therein, design potential solutions, and evaluate their impact;
2. To prepare students for the workplace by fostering their ability to participate in teams, understand and practice interpersonal and organizational behaviors, and communicate their solutions and recommendations effectively through written, oral, and electronic presentations;
3. To familiarize students with the historical development of industrial engineering tools and techniques and with the contemporary state of the art, and to instill the need for lifelong learning within their profession; and
4. To instill in our students an understanding of ethical issues and professional and managerial responsibilities.

Operations Research
The operations research program is one of several applied science programs offered at the School. At the undergraduate level, it offers basic courses in probability, statistics, applied mathematics, simulation, and optimization as well as more professionally oriented operations research courses. The curriculum is well suited for students with an aptitude for mathematics applications.

It prepares graduates for professional employment as operations research analysts, e.g., with management consultant and financial service organizations, as well as for graduate studies in operations research or business. It is flexible enough to be adapted to the needs of future medical and law students.
## INDUSTRIAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

<table>
<thead>
<tr>
<th>Semester I</th>
<th>Semester II</th>
<th>Semester III</th>
<th>Semester IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mathematics</strong></td>
<td><strong>Mathematics</strong></td>
<td><strong>APMA E2000 (4) and E2001 (0)</strong></td>
<td><strong>Linear algebra (3)</strong></td>
</tr>
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<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>Chemistry or physics lab: PHYS UN1404 (2) or PHYS UN1408 (2) or CHEM UN1500 (3) or CHEM UN1507 (3) or CHEM UN3085 (4) or</td>
<td></td>
</tr>
<tr>
<td><strong>Physics (three tracks, choose one)</strong></td>
<td><strong>Physics (three tracks, choose one)</strong></td>
<td><strong>Physics (three tracks, choose one)</strong></td>
<td><strong>Physics (three tracks, choose one)</strong></td>
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<tr>
<td>UN1401 (3)</td>
<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td><strong>Physics (three tracks, choose one)</strong></td>
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<tr>
<td>UN2001 (4.5)</td>
<td>UN2002 (4.5)</td>
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<td></td>
</tr>
<tr>
<td><strong>Chemistry (choose one course)</strong></td>
<td><strong>Chemistry (choose one course)</strong></td>
<td><strong>Chemistry (choose one course)</strong></td>
<td><strong>Chemistry (choose one course)</strong></td>
</tr>
<tr>
<td>UN1403 (3) or UN1404 (3) or UN1604 (3.5) or UN2004 (3.5)</td>
<td><strong>Chemistry or physics lab: PHYS UN1404 (2) or PHYS UN1408 (2) or CHEM UN1500 (3) or CHEM UN1507 (3) or CHEM UN3085 (4) or</strong></td>
<td><strong>Physics (three tracks, choose one)</strong></td>
<td><strong>Physics (three tracks, choose one)</strong></td>
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<td><strong>University Writing</strong></td>
<td><strong>University Writing</strong></td>
<td><strong>University Writing</strong></td>
</tr>
<tr>
<td>CC1010 (3) either semester</td>
<td>HUMA CC1001, COCI CC1101, or Global core (3–4)</td>
<td>HUMA CC1002, COCI CC1102, or Global core (3–4)</td>
<td>HUMA UN1021 or UN1023 (3) either semester</td>
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<tr>
<td><strong>Required Non-technical Electives</strong></td>
<td><strong>Required Non-technical Electives</strong></td>
<td><strong>Required Non-technical Electives</strong></td>
<td><strong>Required Non-technical Electives</strong></td>
</tr>
<tr>
<td>ECON UN1105 (4) and UN1155 recitation (0) either semester</td>
<td><strong>Required Non-technical Electives</strong></td>
<td><strong>Required Non-technical Electives</strong></td>
<td><strong>Required Non-technical Electives</strong></td>
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<td><strong>First- and Second- Year Dept. Requirements</strong></td>
<td><strong>First- and Second- Year Dept. Requirements</strong></td>
<td><strong>First- and Second- Year Dept. Requirements</strong></td>
<td><strong>First- and Second- Year Dept. Requirements</strong></td>
</tr>
<tr>
<td>IEOR E3658 (3) either semester</td>
<td><strong>First- and Second- Year Dept. Requirements</strong></td>
<td><strong>First- and Second- Year Dept. Requirements</strong></td>
<td><strong>First- and Second- Year Dept. Requirements</strong></td>
</tr>
<tr>
<td><strong>Computer Science (two tracks, choose one)</strong></td>
<td><strong>Computer Science (two tracks, choose one)</strong></td>
<td><strong>Computer Science (two tracks, choose one)</strong></td>
<td><strong>Computer Science (two tracks, choose one)</strong></td>
</tr>
<tr>
<td>1. COMS W1004 (3) and COMS W3134 (3)</td>
<td>1. COMS W1004 (3) and COMS W3134 (3)</td>
<td>1. COMS W1004 (3) and COMS W3134 (3)</td>
<td>1. COMS W1004 (3) and COMS W3134 (3)</td>
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<tr>
<td>2. COMS W1007 (3) and COMS W3137 (4)</td>
<td>2. COMS W1007 (3) and COMS W3137 (4)</td>
<td>2. COMS W1007 (3) and COMS W3137 (4)</td>
<td>2. COMS W1007 (3) and COMS W3137 (4)</td>
</tr>
<tr>
<td><strong>Physical Education</strong></td>
<td><strong>Physical Education</strong></td>
<td><strong>Physical Education</strong></td>
<td><strong>Physical Education</strong></td>
</tr>
<tr>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
<td><strong>Physical Education</strong></td>
<td><strong>Physical Education</strong></td>
</tr>
<tr>
<td><strong>The Art of Engineering</strong></td>
<td><strong>The Art of Engineering</strong></td>
<td><strong>The Art of Engineering</strong></td>
<td><strong>The Art of Engineering</strong></td>
</tr>
<tr>
<td>ENGI E1102 (4) either semester</td>
<td><strong>The Art of Engineering</strong></td>
<td><strong>The Art of Engineering</strong></td>
<td><strong>The Art of Engineering</strong></td>
</tr>
</tbody>
</table>

1. The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101 or COMS W3251.
2. The department encourages students to select sequence 1 or 2. ENGI E1006 (3) and COMS W3186 (3) may be substituted in place of sequence 1 or 2.

## INDUSTRIAL ENGINEERING: THIRD AND FOURTH YEARS

<table>
<thead>
<tr>
<th>Semester V</th>
<th>Semester VI</th>
<th>Semester VII</th>
<th>Semester VIII</th>
</tr>
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<tbody>
<tr>
<td><strong>Required Courses</strong></td>
<td><strong>Required Courses</strong></td>
<td><strong>Required Courses</strong></td>
<td><strong>Required Courses</strong></td>
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<tr>
<td>IEOR E3106 (3) Stochastic systems and applications</td>
<td>IEOR E3402 (4) Production &amp; inventory planning</td>
<td>IEOR E4003 (3) Corporate finance for eng</td>
<td>IEOR E4405 (3) Scheduling</td>
</tr>
<tr>
<td>IEOR E3608 (3) Foundations of optimization</td>
<td>IEOR E3609 (3) Advanced optimization</td>
<td>IEOR E4207 (3) Human factors</td>
<td>IEOR E4510 (3) Project management</td>
</tr>
<tr>
<td>IEOR E4307 (3) Statistics and data analysis</td>
<td>IEOR E4405 (3) Corporate finance for eng</td>
<td><strong>Choose One:</strong></td>
<td><strong>Choose One:</strong></td>
</tr>
<tr>
<td>COMS W4110(3)</td>
<td>IEOR E4207 (3) Human factors</td>
<td>IEOR E4505 (3) OR in public policy</td>
<td>IEOR E4505 (3) OR in public policy</td>
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<tr>
<td><strong>Electives</strong></td>
<td><strong>Electives</strong></td>
<td><strong>Electives</strong></td>
<td><strong>Electives</strong></td>
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<tr>
<td><strong>Non-technical</strong></td>
<td><strong>Non-technical</strong></td>
<td><strong>Non-technical</strong></td>
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<tr>
<td>Students must complete the 27-point requirement. Please refer to page 9</td>
<td><strong>Non-technical</strong></td>
<td><strong>Non-technical</strong></td>
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<tr>
<td><strong>Industrial Engineering</strong></td>
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<td>3</td>
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<td><strong>Total Estimated Points</strong></td>
<td><strong>Total Estimated Points</strong></td>
<td><strong>Total Estimated Points</strong></td>
<td><strong>Total Estimated Points</strong></td>
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<tr>
<td>15</td>
<td>14</td>
<td>15</td>
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</table>

1. Taking required courses later than the prescribed semester is not permitted.
2. 9 points total. Complete list is available at ieor.columbia.edu.
# Operations Research Program: First and Second Years

<table>
<thead>
<tr>
<th>Semester</th>
<th>Mathematics</th>
<th>Physics</th>
<th>Chemistry</th>
<th>University Writing</th>
<th>Required Non-Technical Electives</th>
<th>First- and Second-Year Dept. Requirements</th>
<th>Computer Science</th>
<th>Physical Education</th>
<th>The Art of Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>MATH UN1101 (3)</td>
<td>UN1401 (3)</td>
<td>UN1403 (3) or UN1404 (3) or UN1604 (3.5) or UN2045 (3.5)</td>
<td>CC1010 (3) either semester</td>
<td>ECON UN1105 (4) and UN1155 recitation (0) or HUMA CC1001, COOG CC1010, or Global Core (3–4)</td>
<td>ECON UN1001 (1) or UN1002 (1)</td>
<td>COMS W1004 (3) and COMS W3134 (3) or COMS W1007 (3) and COMS W3137 (4)</td>
<td>ENGI E1102 (4) either semester</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>MATH UN1102 (3)</td>
<td>UN2801 (4.5) or UN1602 (3.5)</td>
<td>UN1601 (3.5) or UN1501 (3) or UN6504 (3.5) or UN2045 (3.5)</td>
<td>HUMA CC1002, COOG CC1020, or Global Core (3–4)</td>
<td>UN1002 (1)</td>
<td>1. COMS W1004 (3) and COMS W3134 (3) or 2. COMS W1007 (3) and COMS W3137 (4)</td>
<td>1. IEOR E3658 (3) either semester</td>
<td>UN1001 (1)</td>
<td>ENGI E1102 (4) either semester</td>
</tr>
</tbody>
</table>

1. The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101 or COMS W3251.
2. The department encourages students to select sequence 1 or 2. ENGI E1006 (3) and COMS W3136 (3) may be substituted in place of sequence 1 or 2.

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# Operations Research: Third and Fourth Years

<table>
<thead>
<tr>
<th>Semester</th>
<th>Required Courses</th>
<th>Electives</th>
<th>Total Estimated Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>IEOR E3105 (3) Stochastic systems and applications</td>
<td>IEOR E4003 (3) Corporate finance for eng.</td>
<td>12</td>
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<tr>
<td></td>
<td>IEOR E3608 (3) Foundation of optimization</td>
<td>IEOR E4407 (3) Game theoretic models of operations</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>IEOR E4307 (3) Statistics and data analysis</td>
<td>IEOR E4505 (3) Scheduling</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>COMS W4111 (3) Database systems</td>
<td>Choose one: IEOR E4505: Operations research for public policy</td>
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<tr>
<td></td>
<td></td>
<td>IEOR E4507: Healthcare operations management</td>
<td>6</td>
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<tr>
<td></td>
<td></td>
<td>IEOR E4650: Business analytics</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IEOR E4700: Introduction to FE</td>
<td>6</td>
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</tbody>
</table>

1. Taking required courses later than the prescribed semester is not permitted.
2. 12 points total. At least two technical electives must be chosen from IEOR; the complete list is available at ieor.columbia.edu.
# OPERATIONS RESEARCH PROGRAM: ANALYTICS:
## FIRST AND SECOND YEARS

<table>
<thead>
<tr>
<th>Semester</th>
<th>Mathematics</th>
<th>Physics</th>
<th>Chemistry</th>
<th>University Writing</th>
<th>Required Nontechnical Electives</th>
<th>First- and Second-Year Dept. Requirements</th>
<th>Computer Science</th>
<th>Physical Education</th>
<th>The Art of Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>MATH UN1101 (3)</td>
<td>UN1401 (3)</td>
<td>UN403 (3) or UN1404 (3) or UN1604 (3.5) or UN2045 (3.5)</td>
<td></td>
<td></td>
<td>IEOE E3658 (3) either semester</td>
<td></td>
<td>UN1001 (1)</td>
<td>ENGI E1102 (4) either semester</td>
</tr>
<tr>
<td>II</td>
<td>MATH UN1102 (3)</td>
<td>UN1402 (3)</td>
<td>UN1602 (3.5)</td>
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<td></td>
<td>ORCA E2500 (3) any semester</td>
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<td>UN1002 (1)</td>
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<td>UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
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<tr>
<td>III</td>
<td>APMA E2000 (4) and E2001 (0)</td>
<td>Chemistry or physics lab:</td>
<td></td>
<td>HUMA CC1001,</td>
<td>HUMA CC1002,</td>
<td>IEDR E3658 (3) either semester</td>
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<td>COCI CC1101,</td>
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<td>or Global Core (3–4)</td>
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<td>Linear algebra (3)</td>
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</tbody>
</table>

1. The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101 or COMS W3251.
2. The department encourages students to select sequence 1 or 2. ENGI E1006 (3) and COMS W3136 (3) may be substituted in place of sequence 1 or 2.

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# OPERATIONS RESEARCH: ANALYTICS:
## THIRD AND FOURTH YEARS

<table>
<thead>
<tr>
<th>Semester</th>
<th>Required Courses</th>
<th>NonTech</th>
<th>Analytics</th>
<th>Total Estimated Points</th>
</tr>
</thead>
<tbody>
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<td>V</td>
<td>IEOR E3106 (3)</td>
<td>Students must complete the 27-point requirement. Please refer to page 9.</td>
<td>Choose six: Advanced Data Analytics Elective (2 or more) Operations Research Elective (2 or more) Management Elective (1) Breadth Elective (max of 1)</td>
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<tr>
<td>VI</td>
<td>IEOR E3108 (3)</td>
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<tr>
<td>VII</td>
<td>IEOR E4307 (3)</td>
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<td>12</td>
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<tr>
<td>VIII</td>
<td>IEOR E4212 (3)</td>
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<td>12</td>
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</table>

1. Taking required courses later than the prescribed semester is not permitted.
2. 18 points total. At least two technical electives must be chosen from IEOR; the complete list is available at ieor.columbia.edu.
### OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: FIRST AND SECOND YEARS

<table>
<thead>
<tr>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATHEMATICS</strong></td>
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<td>Linear algebra (3)¹</td>
</tr>
<tr>
<td>MATH UN101 (3)</td>
<td>MATH UN102 (3)</td>
<td>APMA E2000 (4) and E2001 (0)</td>
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<td><strong>PHYSICS</strong></td>
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<td>UN401 (3)</td>
<td>UN402 (3)</td>
<td>Chemistry or physics lab:</td>
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<td>UN1801 (4.5)</td>
<td>UN2802 (4.5)</td>
<td>PHYS UN194 (2) or</td>
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<td>PHYS UN3081 (2) or</td>
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<td>CHEM UN500 (3) or</td>
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<td>CHEM UN507 (3) or</td>
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<td>CHEM UN3085 (4) or</td>
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<tr>
<td><strong>CHEMISTRY</strong></td>
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<tr>
<td>(choose one course)</td>
<td>UN403 (3) or UN404 (3) or UN504 (3.5) or UN2045 (3.5)</td>
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<td></td>
</tr>
<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
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<td>CC1010 (3)</td>
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<tr>
<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
<td></td>
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<tr>
<td>ECON UN1105 (4)</td>
<td>ECON UN1155 recitation (0)</td>
<td>HUMA CC1001, COCI CC1101</td>
<td>HUMA CC1002, COCI CC1102</td>
</tr>
<tr>
<td></td>
<td>other semester</td>
<td>or Global Core (3–4)</td>
<td>or Global Core (3–4)</td>
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<tr>
<td><strong>FIRST- AND SECOND-YEAR DEPT. REQUIREMENTS</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>IEOR E3658 (3) other semester</td>
</tr>
<tr>
<td><strong>COMPUTER SCIENCE</strong> (two tracks, choose one)</td>
<td></td>
<td></td>
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<tr>
<td>1. COMS W1004 (3) and COMS W3134 (3) or 2. COMS W1007 (3) and COMS W3137 (4)²</td>
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</tr>
<tr>
<td><strong>PHYSICAL EDUCATION</strong></td>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
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<tr>
<td><strong>THE ART OF ENGINEERING</strong></td>
<td>ENGI E1102 (4) other semester</td>
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</tbody>
</table>

¹ The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101 or COMS W3251.
² The department encourages students to select sequence 1 or 2. ENGI E1006 (3) and COMS W3136 (3) may be substituted in place of sequence 1 or 2.

### OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: THIRD AND FOURTH YEARS

<table>
<thead>
<tr>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REQUIRED COURSES¹</strong></td>
<td>ECON UN2211 (4) Microeconomics</td>
<td>ECON 3213 (4) Macroeconomics</td>
<td>IEOR E4003 (3) Corporate finance for eng.</td>
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<tr>
<td></td>
<td>IEOR E3106 (3) Stochastic systems and applications</td>
<td>IEOR E3402 (4) Production &amp; inventory planning</td>
<td>Choose one:</td>
</tr>
<tr>
<td></td>
<td>IEOR E3608 (3) Foundations of optimization</td>
<td>IEOR E3404 (4) Simulation</td>
<td>IEOR E4550 (3) Entrepreneurial business creation</td>
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<tr>
<td></td>
<td>IEOR E4307 (3) Statistics and data analysis</td>
<td>IEOR E3609 (3) Advanced optimization</td>
<td>or IEOR E4998 (3) Managing technological innovations</td>
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<tr>
<td></td>
<td>COMS W4111(3) Database systems</td>
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<td>Choose one:</td>
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<td></td>
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<td>IEOR E4510 (3) Project management or</td>
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<td>IEOR E4506 (3) Designing digital operating models or</td>
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<tr>
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<td>IEOR E4505 (3) Business analytics</td>
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<td><strong>NONTECH</strong></td>
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<td>Students must complete the 27-point requirement. Please refer to page 9.</td>
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<tr>
<td><strong>TECH²</strong></td>
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<td><strong>MANAGEMENT¹</strong></td>
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<tr>
<td>3</td>
<td>6</td>
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<td><strong>TOTAL ESTIMATED POINTS</strong></td>
<td>16</td>
<td>18</td>
<td>18</td>
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¹ Taking required courses later than the prescribed semester is not permitted.
² 12 points total. At least two technical electives must be chosen from IEOR; the complete list is available at ieor.columbia.edu.
³ 9 points total.
## OPERATIONS RESEARCH: FINANCIAL ENGINEERING:
### FIRST AND SECOND YEARS

<table>
<thead>
<tr>
<th>Semester</th>
<th>Mathematics</th>
<th>Physics</th>
<th>Chemistry</th>
<th>University Writing</th>
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<tr>
<td>I</td>
<td>MATH UN101 (3)</td>
<td>UN1401 (3)</td>
<td>UN403 (3.5)</td>
<td>CC1010 (3) either semester</td>
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<td>II</td>
<td>MATH UN102 (3)</td>
<td>UN1402 (3)</td>
<td>UN1404 (3.5)</td>
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<td>Phys or chemistry lab: PHYS UN1494 (3) or PHYS UN1081 (2) or CHEM UN1500 (3) or CHEM UN1007 (3) or CHEM UN1086 (3)</td>
<td>UN1404 (3.5) or UN1004 (3.5) or UN2045 (3.5)</td>
<td>HUMA CC1002, COCI CC1102, or Global Core (3–4)</td>
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<td>UN1500 (3.5)</td>
<td>HUMA UN1121 or UN1123 (3) either semester</td>
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<td>UN2801 (4.5)</td>
<td>IEOR E3658 (3) either semester</td>
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<td>UN2802 (4.5)</td>
<td>HUMA UN1121, COCI CC1101, or Global Core (3–4)</td>
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<td>FIRST- AND SECOND-YEAR DEPT. REQUIREMENTS</td>
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<td>ECON UN105 (4) and UN1155 recitation (0) either semester</td>
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<td>IEOR E3106 (3) Stochastic systems and applications</td>
</tr>
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<td>IEOR E3608 (3) Foundations of optimization</td>
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<td></td>
<td>IEOR E4003 (3) Corporate finance for eng</td>
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<td>IEOR E4307 (3) Statistics and data analysis</td>
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<td></td>
<td>COMS W4111(3) Database systems</td>
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<td></td>
<td></td>
<td></td>
<td>ENGII E1102 (4) either semester</td>
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<td></td>
<td></td>
<td>IEOR E3609 (3) Advanced optimization</td>
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<td>IEOR E4307 (3) Corporate finance for eng</td>
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<td>IEOR E4700 (3) Intro. to FE</td>
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### OPERATIONS RESEARCH: FINANCIAL ENGINEERING:
### THIRD AND FOURTH YEARS

<table>
<thead>
<tr>
<th>Semester</th>
<th>Required Courses</th>
<th>Electives</th>
<th>Total Estimated Points</th>
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<tbody>
<tr>
<td>V</td>
<td>IEOR E3106 (3) Stochastic systems and applications</td>
<td>ECON UN3221 (4) Microeconomics</td>
<td>18</td>
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<tr>
<td></td>
<td>IEOR E3608 (3) Foundations of optimization</td>
<td>IEOR E4302 (4) Production &amp; inventory planning</td>
<td>17</td>
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<tr>
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<td>IEOR E4003 (3) Corporate finance for eng</td>
<td>IEOR E4304 (4) Simulation</td>
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<tr>
<td></td>
<td>IEOR E4307 (3) Statistics and data analysis</td>
<td>IEOR E3609 (3) Advanced optimization</td>
<td>20</td>
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<tr>
<td></td>
<td>COMS W4111(3) Database systems</td>
<td>IEOR E4700 (3) Intro. to FE</td>
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<td></td>
<td>ENGII E1102 (4) either semester</td>
<td>ECON E3402 (4) Intro. to econometrics either semester</td>
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<tr>
<td>VI</td>
<td>ECON UN3221 (4) Microeconomics</td>
<td>IEOR E4630 (3) Asset allocation</td>
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<tr>
<td></td>
<td>IEOR E4407 (3) Game theoretic models of operations</td>
<td>IEOR E4630 (3) Asset allocation</td>
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</tr>
<tr>
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<td>IEOR E4500 (3) Applications prog. for FE</td>
<td>IEOR E4630 (3) Asset allocation</td>
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<tr>
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<td>IEOR E4620 (3) Pricing models for FE</td>
<td>IEOR E4630 (3) Asset allocation</td>
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<tr>
<td></td>
<td>ECON E3402 (4) Intro. to econometrics either semester</td>
<td>IEOR E4630 (3) Asset allocation</td>
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</tr>
</tbody>
</table>

1. The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101 or COMS W3251.
2. The department encourages students to select sequence 1 or 2. ENGII E1006 (3) and COMS W3336 (3) may be substituted in place of sequence 1 or 2.

**Notes:**
- Taking required courses later than the prescribed semester is not permitted.
- 9 points total. The complete list is available at ieor.columbia.edu.
Operations Research: Engineering Management Systems

This operations research option is designed to provide students with an understanding of contemporary technology and management. It is for students who are interested in a technical-management background rather than one in a traditional engineering field. It consists of required courses in industrial engineering and operations research, economics, business, and computer science, intended to provide a foundation for dealing with engineering and management systems problems. Elective courses are generally intended to provide a substantive core in at least one technology area and at least one management area.

Due to the flexibility of this option, it can incorporate the varied educational needs of preprofessional students interested in law, medicine, business, and finance. In addition, most students are encouraged to add a minor in economics or computer science to their standard course schedules.

Operations Research: Analytics

The analytics concentration within the operations research program seeks to train students to leverage advanced quantitative models, algorithms, and data for making actionable decisions to improve business operations. Examples include staffing and scheduling at hospitals, ride matching and pricing for on-demand car services, personalized promotions in online retail, and smarter energy consumption. Students are provided with a rigorous exposure to optimization and stochastic modeling, as well as machine learning and data analysis tools for predictive modeling and prescriptive analytics. Elective in the areas of healthcare, marketing, transportation, deep learning, and many others further enrich students with domain expertise, and provide many opportunities to work directly with data on real-world problems.

Operations Research: Financial Engineering

The operations research concentration in financial engineering is designed to provide students with an understanding of the application of engineering methodologies and quantitative methods to finance. Financial engineering is a multidisciplinary field integrating financial theory with economics, methods of engineering, tools of mathematics, and practice of programming. Students graduating with this concentration are prepared to enter careers in securities, banking, financial management, and consulting industries, and fill quantitative roles in corporate treasury and finance departments of general manufacturing and service firms.

Students who are interested in pursuing the rigorous concentration in financial engineering must demonstrate proficiency in calculus, computer programming, linear algebra, ordinary differential equations, probability, and statistics.

Undergraduate Advanced Track

The undergraduate advanced track is designed for advanced undergraduate students with the desire to pursue further higher education after graduation. Students with a minimum cumulative GPA of 3.4 and faculty approval have the opportunity to participate. Students are invited to apply to the track upon the completion of their sophomore year. Advanced track students are required to take higher-level IEOR courses, including the following:

IEOR E4004 instead of IEOR E3608
IEOR E4106 instead of IEOR E3106
IEOR E4403 instead of IEOR E4003
IEOR E4404 instead of IEOR E3404
MATH UN2500

Students successfully completing the requirements of the undergraduate advanced track will receive recognition on their academic record.

Minors

A number of minors are available for students wishing to add them to their programs. These minors are described starting on page 205 of this bulletin.

IEOR program students may want to consider minors in economics or computer science. In addition, operations research and engineering and management systems majors may elect to minor in industrial engineering, and industrial engineering majors may elect to minor in operations research.

The department does not offer a minor in engineering management systems or financial engineering.

GRADUATE PROGRAMS

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

MASTER OF SCIENCE PROGRAMS

The Department of Industrial Engineering and Operations Research offers courses and M.S. programs in (1) financial engineering on a full-time basis only; (2) management science and engineering on a full-time basis only; (3) business analytics on a full-time basis only; (4) industrial engineering on either a full- or part-time basis; and (5) operations research on either a full- or part-time basis. Both the Department’s M.S. programs in Business Analytics and Management Science and Engineering is offered in conjunction with Columbia Business School. Lastly, the Department and Columbia Business School offer a combined M.S./M.B.A. degree program in industrial engineering.

All degree program applicants are required to take the Aptitude Tests of the Graduate Record Examination (GRE). M.S./M.B.A. candidates are also required to take the Graduate Management Admissions Test (GMAT). A minimum grade-point average of 3.0 (B) or its equivalent in an undergraduate engineering program is required for admission to the M.S. programs. At a minimum, students are expected, on entry, to have completed courses in ordinary differential equations, linear algebra, probability, and a programming language such as C, Java, or Python.

The Department requires that M.S. students achieve grades of B– or higher in each of the fundamental core courses in the discipline of study. Poor performance in core courses is indicative of inadequate preparation and is very likely to lead to serious problems in completing the program. As a result, students failing to meet this criterion...
### Business Analytics (36 points)

#### Required Core Courses (18 points)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEOR E4004</td>
<td>Optimization models and methods (first fall semester)</td>
</tr>
<tr>
<td>IEOR E4011</td>
<td>Probability, statistics and simulation (first fall semester)</td>
</tr>
<tr>
<td>IEOR E4502</td>
<td>Python for analytics (0 pt) (first fall semester)</td>
</tr>
<tr>
<td>IEOR E4523</td>
<td>Data analytics (fall semester)</td>
</tr>
<tr>
<td>ENGI E4000</td>
<td>Professional development (0 pt) (first fall semester, yearlong)</td>
</tr>
<tr>
<td>IEOR E4650</td>
<td>Business analytics (spring semester)</td>
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<tr>
<td>IEOR E4524</td>
<td>Analytics in practice (spring semester)</td>
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<tr>
<td>IEOR E4599</td>
<td>MSBA quantitative bootcamp (0 pt)</td>
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<tr>
<td>MRKT B9651</td>
<td>Marketing analytics (first fall semester)</td>
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</tbody>
</table>

#### Concentration Courses (Financial Analytics & Financial Technology (FinTech), Marketing Analytics, Healthcare Analytics, and Analytics Algorithms & Methodology) (18 points)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEOR E4106</td>
<td>Stochastic models</td>
</tr>
<tr>
<td>IEOR E4500</td>
<td>Applications programming for Financial Engineering</td>
</tr>
<tr>
<td>IEOR E4525</td>
<td>Machine learning for FE &amp; OR</td>
</tr>
<tr>
<td>IEOR E4574</td>
<td>Technology innovation in financial services (1.5)</td>
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<tr>
<td>IEOR E4742</td>
<td>Deep learning for FE &amp; OR</td>
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<tr>
<td>IEOR E4725</td>
<td>Big data in finance</td>
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<tr>
<td>MRKT B8649</td>
<td>Pricing strategies</td>
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<tr>
<td>DROM B8106</td>
<td>Operations strategy</td>
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<tr>
<td>DROM B8116</td>
<td>Risk management</td>
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<tr>
<td>DROM MGMT B8510</td>
<td>Managerial negotiations</td>
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<tr>
<td>MRKT B8676</td>
<td>Foundations of innovation</td>
</tr>
<tr>
<td>DROM B8816</td>
<td>Quantitative pricing and revenue analytics</td>
</tr>
<tr>
<td>DROM B9122</td>
<td>Computing for business research</td>
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#### Marketing Analytics (9 points)

<table>
<thead>
<tr>
<th>Course Code</th>
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<tbody>
<tr>
<td>IEOR E4407</td>
<td>Game theoretic models of operations</td>
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<tr>
<td>IEOR E4506</td>
<td>Designing digital operating models</td>
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<tr>
<td>IEOR E4312</td>
<td>Application of OR &amp; AI techniques in marketing (1.5)</td>
</tr>
<tr>
<td>IEOR E4502</td>
<td>Innovate using design thinking (Blockweek)</td>
</tr>
<tr>
<td>IEOR E4601</td>
<td>Dynamic pricing and revenue management</td>
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<tr>
<td>DROM B8122</td>
<td>Game-theoretic business strategy</td>
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<tr>
<td>DROM B8123</td>
<td>Demand and supply analytics</td>
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<tr>
<td>DROM B8131</td>
<td>Sports analytics</td>
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<tr>
<td>DROM/MKT B8510</td>
<td>Managerial negotiations</td>
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<tr>
<td>MRKT B8607</td>
<td>Strategic consumer insights</td>
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<tr>
<td>MRKT B8608</td>
<td>New product development</td>
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<tr>
<td>MRKT B8617</td>
<td>Marketing research and analytics</td>
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<tr>
<td>MRKT B8623</td>
<td>Intro to product management (1.5)</td>
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<tr>
<td>MRKT B8625</td>
<td>Winning strategic capabilities</td>
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<tr>
<td>MRKT B8679</td>
<td>Digital marketing</td>
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<tr>
<td>MRKT B8681</td>
<td>Advanced marketing strategy</td>
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<tr>
<td>MRKT B8683</td>
<td>Marketing models</td>
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<tr>
<td>DROM B9112</td>
<td>Computing for business research</td>
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<tr>
<td>DROM B9127</td>
<td>Online marketplaces</td>
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<tr>
<td>MRKT B9613</td>
<td>Mathematical models in marketing</td>
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<tr>
<td>MRKT B9656</td>
<td>Customer management: concepts and tools (1.5)</td>
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#### Healthcare Analytics (9 points)

<table>
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<tr>
<td>IEOR E4108/DROM B8108</td>
<td>Supply chain analytics</td>
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<td>IEOR E4405</td>
<td>Scheduling</td>
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<td>IEOR E4505</td>
<td>Operations research in public policy</td>
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<tr>
<td>IEOR E4507</td>
<td>Health care operations management</td>
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<tr>
<td>IEOR E4520</td>
<td>Applied systems engineering</td>
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<tr>
<td>IEOR E4521</td>
<td>Systems engineering tools and methods (OR)</td>
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<td>IEOR E4540</td>
<td>Data mining for engineers</td>
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<td>DROM B8105</td>
<td>Healthcare analytics (1.5)</td>
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<tr>
<td>DROM B8107</td>
<td>Service operations</td>
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<tr>
<td>DROM B8128</td>
<td>Healthcare investment and entrepreneurship HGT and services</td>
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<tr>
<td>DROM B8132</td>
<td>Digital health care systems</td>
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<tr>
<td>DROM/MSBA B8510</td>
<td>Managerial negotiations</td>
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<tr>
<td>MRKT B8692</td>
<td>Pharmaceutical drug commercialization: strategy &amp; practice (1.5)</td>
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<tr>
<td>DROM B8832</td>
<td>U.S. health care system</td>
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<tr>
<td>MRKT B9656</td>
<td>Customer management: concepts and tools (1.5)</td>
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#### Analytics Algorithms & Methodology (9 points)

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<tr>
<td>COMS W4111</td>
<td>Introduction to databases</td>
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<td>CSOR W4231</td>
<td>Analysis of algorithms</td>
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<tr>
<td>IEOR E4407</td>
<td>Game theoretic models of operations</td>
</tr>
<tr>
<td>IEOR E4418</td>
<td>Transportation analytics &amp; logistics</td>
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<tr>
<td>IEOR E4525</td>
<td>Machine learning for FE &amp; OR</td>
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<tr>
<td>IEOR E4526</td>
<td>Analytics on the cloud</td>
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<td>IEOR E4540</td>
<td>Data mining for engineers</td>
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<td>DROM B8110</td>
<td>Business analytics strategy</td>
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<td>DROM B8111</td>
<td>Analytics for business research</td>
</tr>
<tr>
<td>DROM B8127</td>
<td>Big immersion seminar—big data (1.5 pts)</td>
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<td>DROM B8130</td>
<td>Applied statistics and data analytics</td>
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<td>MRKT B9160</td>
<td>Applied multivariate statistics</td>
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<td>MRKT B9608</td>
<td>Experimental design &amp; analysis for behavioral research</td>
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<td>MRKT B9616</td>
<td>Bayesian modeling &amp; computation</td>
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<tr>
<td>MRKT B9652</td>
<td>MS marketing models</td>
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<td>MRKT B9653</td>
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<tr>
<td>MRKT B9654</td>
<td>MS artificial intelligence</td>
</tr>
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#### Additional Details

The M.S. program in Business Analytics (MSBA) offered by the IEOR Department in partnership with Columbia Business School. This program is formed and structured following many interactions with corporations, alumni, and students. It emphasizes on developing new insights and understanding of business performance using data, statistical and quantitative analysis, and exploratory and predictive modeling to help make actionable decisions and to improve business operations. Students pursuing this degree program are provided with rigorous exposure to optimization and stochastic modeling, and a deep coverage of applications in the areas of analytics. The role of analytics has grown increasingly critical in business, health care, government, and many other sectors of the economy.

It is a 36-credit degree STEM-designated program (equivalent of 12 three-credit courses), assuming adequate preparation in probability and statistics, with students taking at least six courses (18 credits) within the IEOR Department, and four to six courses (18 credits) within the School of Engineering, the School of International and Public Affairs, the Law School, or the Departments of Economics, Mathematics, and Statistics. Additional details are available on the MSBA website: msba.engineering.columbia.edu/content/curriculum.

### Financial Engineering

The M.S. program in Financial Engineering is offered on a full time basis only. Financial Engineering is intended to provide a unique technical background for students interested in pursuing career opportunities in financial analysis and risk management.
In addition to the basic requirements for graduate study, students are expected, on entry, to have attained a high level of mathematical and computer programming skills, particularly in probability, statistics, linear algebra, and the use of a programming language such as C, Python or JAVA. Previous professional experience is highly desirable but not required.

Graduate studies in Financial Engineering consists of 36 points (12 courses), starting the fall semester. Students may complete the program in May, August, or December of the following year. The requirements include six required core courses and additional elective courses chosen from a variety of departments or schools at Columbia. The six required core courses for Financial Engineering are IEOR E4007, E4701, E4703, E4706, E4707, and E4709. In addition, students are required to attend IEOR E4798 Financial Engineering Seminar and submit learning journals.

Financial Engineering has seven concentrations: (1) Asset Management; (2) Computation and Programming; (3) Computational Finance and Trading Systems; (4) Derivatives; (5) Finance and Economics; (6) Financial Technology; and (7) Machine Learning for Financial Engineering. A sample schedule is available in the Department office and on the IEOR website: ieor.columbia.edu. Students select electives from a group of specialized offerings in both the fall and spring terms. They may select from a variety of approved electives from the Department, Columbia Business School, and the Graduate School of Arts and Sciences.

### Management Science and Engineering

Management Science and Engineering (MS&E), offered by the IEOR Department in partnership with Columbia Business School, is the first such program between Columbia Engineering and Columbia Business School. It reflects the next logical step in the long-standing close collaboration between the IEOR Department at the Engineering School and the Decision, Risk, and Operations (DRO) Division at the Business School. Coursework emphasizes both management and engineering perspectives in solving problems, making decisions, and managing risks in complex systems. Students pursuing this specialization are provided with a rigorous exposure to optimization and stochastic modeling, and a deep coverage of applications in the areas of operations engineering and management.

In addition to the core and semi-core requirements, Management Science and Engineering has six concentrations: (1) Operations and Analytics; (2) Pricing and Revenue Management; (3) Entrepreneurship and Innovation; (4) Logistics and Supply Chain Management; (5) Financial Technology (Fin Tech); and (6) Healthcare Management. Additional details regarding these concentrations are available on the MS&E website: mse.ieor.columbia.edu/content/mse-concentrations.

Graduates of this program are expected to assume positions as analysts and associates in consulting firms, business analysts in logistics, supply chain, operations, or revenue management departments of large corporations, and as financial analysts in various functions (e.g., risk management) of investment banks, hedge funds, credit-card companies, and insurance firms.

Management Science and Engineering (36 points) can be completed in a single calendar year, in three semesters. Students enter in the fall term and can either finish their coursework at the end of the following August, or alternatively, have the option to take the summer term off (e.g., for an internship) and complete their coursework by the end of the following fall term. Students are required to take the equivalent of 12 3-point courses (36 points).

Students must take at least six

<table>
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<tr>
<th>Financial Engineering (36 points)</th>
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<tr>
<td><strong>Fall Semester</strong> (9 points)³</td>
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<td><strong>Spring Semester</strong> (9 points)³</td>
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<tr>
<td><strong>Summer and/or Fall Semester</strong> (For remaining credits)²</td>
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¹ Students may conclude the program in May, August, or December. Please visit the departmental website (msfe.ieor.columbia.edu) for more information.

² All courses listed are for 3 points, unless stated otherwise.

³ The list of Financial Engineering electives can be found at ieor.columbia.edu/masters-financial-engineering/curriculum.
Graduate studies in Operations Research (18 points) within the IEOR Department, three to six courses at the Business School, and the remaining courses (if any) within the School of Engineering, the School of International and Public Affairs, the Law School, or the Departments of Economics, Mathematics, and Statistics. Students in residence during the summer term can take two to four Business School courses in the third (summer) semester in order to complete their program. Additional details regarding these electives are available in the Departmental office and on the MS&E website: mse.ieor.columbia.edu.

**Industrial Engineering**

Graduate studies in Industrial Engineering enable students with industrial engineering bachelor's degrees to enhance their undergraduate training with studies in special fields such as production planning, inventory control, scheduling, and industrial economics. However, the department also offers a broader master's program for engineers whose undergraduate training is not in industrial engineering. Students may complete the studies on a full-time (12 points per term) or part-time basis.

Industrial Engineers are required to satisfy a core program of graduate courses in production management, probability theory, statistics, simulation, and operations research. Students with B.S. degrees in industrial engineering will usually have satisfied this core in their undergraduate programs. All students must take at least 18 points of graduate work in industrial engineering and at least 30 points of graduate studies at Columbia. Industrial Engineering may include concentrations in: (1) Healthcare Management; (2) Regulated Industries; and (3) Systems Engineering. Additional details regarding these concentrations and electives are available in the Departmental office and on the IEOR website: ieor.columbia.edu.

**Operations Research**

Graduate studies in Operations Research enables students to concentrate their studies in methodological areas such as mathematical programming, stochastic models, and simulation. Students may complete the studies on a full time (12 points per term) or part-time basis.

<table>
<thead>
<tr>
<th>Required Core Courses (12 points)</th>
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<tbody>
<tr>
<td>IEOR E4004 Optimization models and methods (first fall semester)</td>
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<tr>
<td>IEOR E4101 Probability, statistics, and simulation (first fall semester)</td>
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<tr>
<td>IEOR E4102 Stochastic models (spring semester)</td>
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<tr>
<td>IEOR E4111 Operations consulting (starts first fall semester, year-long course)</td>
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<tr>
<td>DROM B8000 Optimization and simulation bootcamp (0 pt)</td>
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<tr>
<th>Semi-Core Courses (DRO, Analysis, and Management Electives 18 points)</th>
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<tr>
<td>IEOR E4650 Business analysis</td>
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<tr>
<td>DROM B8101 Business analytics II (1.5 pt)</td>
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<td>DROM B8105 Healthcare analytics (1.5)</td>
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<tr>
<td>DROM B8106 Operations strategy (1.5 pt)</td>
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<td>DROM B8107 Service operations</td>
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<td>DROM B8110 Business analytics strategy</td>
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<tr>
<td>DROM B8116 Risk management</td>
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<tr>
<td>DROM B8123 Demand &amp; supply analytics</td>
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<td>DROM B8131 Sports analytics</td>
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<tr>
<td>DROM B8510 Managerial negotiations</td>
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<tr>
<th>Analysis and Management Electives (9 points minimum)</th>
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<tr>
<td>IEOR E4008 Computational discrete optimization</td>
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<tr>
<td>CSOR W4231 Analysis of algorithms I</td>
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<td>IEOR E4405 Scheduling</td>
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<td>IEOR E4407 Game theoretic models of operations</td>
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<td>IEOR E4418 Transportation analytics and logistics</td>
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<td>IEOR E4501 Tools for analytics</td>
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<td>IEOR E4507 Healthcare operations management</td>
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<td>IEOR E4523 Data analytics</td>
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<td>IEOR E4525 Machine learning for financial engineering &amp; operations research</td>
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<td>IEOR E4526 Analytics on the cloud</td>
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<td>IEOR E4540 Data mining for engineering</td>
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<td>IEOR E4532 Visualization &amp; storytelling with data (1.5)</td>
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<td>IEOR E4533 Performance, objectives &amp; results using data analytics (1.5)</td>
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<td>IEOR E4601 Dynamic pricing and revenue optimization</td>
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<td>IEOR E4742 Deep learning for operations research &amp; financial engineering</td>
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<td>DROM B8108 Supply chain analytics</td>
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<th>Analysis Group</th>
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<td>At least one of the following:</td>
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<tr>
<td>IEOR E4412 Quality control and management</td>
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<td>IEOR E4505 Operations research in public policy</td>
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<td>IEOR E4506 Designing digital operating models</td>
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<td>IEOR E4510 Project management</td>
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<tr>
<td>IEOR E4550 Entrepreneurial business creation for engineers</td>
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<td>IEOR E4560 Lean launchpad (weeklong course in mid-January, by application only)</td>
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<td>IEOR E4561 Launch your startup: tech</td>
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<tr>
<td>IEOR E4562 Innovate using design thinking (weeklong course in mid-January, by application only)</td>
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<tr>
<td>IEOR E4570 Entrepreneurship bootcamp for engineers (3-day long course fall or spring semester, by application only)</td>
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<tr>
<td>IEOR E4711 Global capital markets</td>
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<tr>
<td>IEOR E4998 Managing technological innovation and entrepreneurship</td>
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<tr>
<td>FINC B8307 Advanced corporate finance</td>
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<tr>
<td>FINC B8307 Advanced corporate finance</td>
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| Breadth Electives: |
| The breadth electives can be selected from the Business School, the School of Engineering, the School of International and Public Affairs, the Law School, or the Departments of Economics, Mathematics, and Statistics. |
points per term) or part time basis.

Operations Research has eight areas of concentrations, including: (1) Analytics; (2) Decision, Risk, and Analysis; (3) Entrepreneurship and Innovation; (4) Finance and Management; (5) Healthcare Management; (6) Logistics and Supply Chain Management; (7) Machine Learning and Artificial Intelligence; and (8) Optimization. Students may select from a variety of approved electives from the Department, Columbia Business School, and the Graduate School of Arts and Sciences. Additional details regarding these concentrations and electives are available in the Departmental office and on IEOR’s website: ieor.columbia.edu.

JOINT M.S. AND M.B.A.
The Department and Columbia Business School offer a joint M.S. program in Industrial Engineering. Prospective students for this special program must submit separate applications to Columbia Engineering and Columbia Business School and be admitted to both schools for entrance into the joint program.

Admissions requirements are the same as those for the regular M.S. program in Industrial Engineering and for the M.B.A. This joint program is coordinated so that both degrees can be obtained after five terms of full-time study (30 points in two terms while registered in Columbia Engineering and 45 points in three terms while registered in Columbia Business School).

Students in the joint program must complete certain courses by the end of their first year of study. If a substantial equivalent has been completed during undergraduate studies, students should consult with a faculty advisor in order to obtain exemption from a required course.

PH.D. PROGRAM
The IEOR Department offers two Ph.D. programs in (1) Industrial Engineering; and (2) Operations Research. The requirements for the Ph.D. in industrial engineering and operations research are identical. Both programs require the student to complete the qualifying procedure and submit and defend a dissertation based on the candidate's original research, conducted under the supervision of the faculty. The dissertation work may be theoretical or computational or both.

The qualifying procedure consists of three components, including: (1) complete the four core courses during the first year with an average grade of (A-) or above; (2) conduct research during the first summer (ideally starting in Spring or earlier) and present it in a department seminar at the beginning of the third semester; and (3) submit a research report (paper) at the end of the third semester. Students will be reviewed after each component. A student who fails to complete component (1) may be asked to withdraw from the program at the end of the first year.

A student who successfully completes component (1) will typically move on to do summer research, advised by a faculty member in the IEOR Department. In the rare instance the Ph.D. committee is dissatisfied with a student's performance in components (2) and (3), they may be asked to withdraw from the program at the end of the second year.

Doctoral students are also required to take 4 additional Ph.D. courses (possibly in other departments) during the course of the Ph.D. Research credits (IEOR E9101) do not count toward this requirement. It is important to select courses you find interesting while considering your background and in consultation with your academic adviser. Students can consider courses from other departments including Mathematics, Computer Science, Statistics, Economics, and Decision Risk and Operations. Doctoral candidates must obtain a minimum of 60 points of formal course credit beyond the bachelor’s degree. A master’s degree from an accredited institution may be accepted as equivalent to 30 points. A minimum of 30 points beyond the master’s degree must be earned while in residence in the doctoral program. Detailed information regarding the requirements for the doctoral degree may be obtained in the Department office and on IEOR website: ieor.columbia.edu.

COURSES IN INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH
For up-to-date course offerings, please visit ieor.columbia.edu.

IEOR E1000x or y Frontiers in operations research and data analytics
Introductory course for overview of modern approaches and ideas of operations research and data analytics. Through a series of interactive sessions, students engage in activities exploring OR topics with various faculty members from the IEOR department.

IEOR E2261x and y Accounting and finance
3 pts. Lect: 3.
Prerequisite(s): ECON UN1105 Principles of economics. For undergraduates only. Examines the fundamental concepts of financial accounting and finance, from the perspective of both managers and investors. Key topics covered include
principles of accrual accounting; recognizing and recording accounting transactions; preparation and analysis of financial statements; ratio analysis; pro-forma projections; time value of money (present values, future values and interest/discount rates); inflation; discounted-cash-flow (DCF) project evaluation methods; deterministic and probabilistic measures of risk; capital budgeting.

ORCA E2500y Foundations of data science 3 pts. Lect: 3. Prerequisite(s): MATH UN1101 and UN1102. Some familiarity with programming. Designed to provide an introduction to data science for sophomore SEAS majors. Combines three perspectives: inferential thinking, computational thinking, and real-world applications. Given data arising from some real-world phenomenon, how does one analyze that data so as to understand that phenomenon? Teaches critical concepts and skills in computer programming, statistical inference, and machine learning, in conjunction with hands-on analysis of real-world datasets such as economic data, document collections, geographical data, and social networks. At least one project will address a problem relevant to New York City.

IEOR E3106x Stochastic systems and applications 3 pts. Lect: 3. Prerequisite(s): IEOR E3658. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Must be taken during (or before) the fifth semester. Some of the main stochastic models used in engineering and operations research applications: discrete-time Markov chains, Poisson processes, birth and death processes and other continuous Markov chains, renewal reward processes. Applications: queuing, reliability, inventory, and finance. IEOR E3106 must be completed by the fifth term. Only students with special academic circumstances may be allowed to take these courses in alternative semesters with the consultation of CSA and Departmental advisers.

IEOR E3402y Production and inventory planning 4 pts. Lect: 3. Recit: 1. Prerequisite(s): IEOR E3608 and E3658. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Must be taken during (or before) the sixth semester. Inventory management and production planning. Continuous and periodic review models: optimal policies and heuristic solutions, deterministic and probabilistic demands. Material requirements planning. Aggregate planning of production, inventory, and workforce. Multi-echelon integrated production-inventory systems. Production scheduling. Term project. Recitation section required.

IEOR E3404y Simulation modeling and analysis 4 pts. Lect: 4. Prerequisite(s): IEOR E3658 and E4307 or STAT GU4001, and knowledge of a programming language such as Python, C, C++ or Matlab. It is strongly advised that Stochastic modeling (IEOR E3106 or IEOR E4106) be taken before this course. This is an introductory course to simulation, a statistical sampling technique that uses the power of computers to study complex stochastic systems when analytical or numerical techniques do not suffice. The course focuses on discrete-event simulation, a general technique used to analyze a model over time and determine the relevant quantities of interest. Topics covered in the course include the generation of random numbers, sampling from given distributions, simulation of discrete-event systems, output analysis, variance reduction techniques, goodness of fit tests, and the selection of input distributions. The first half of the course is oriented toward the design and implementation of algorithms, while the second half is more theoretical in nature and relies heavily on material covered in prior probability courses. The teaching methodology consists of lectures, recitations, weekly homework, and both in-class and take-home exams. Homework almost always includes a programming component for which students are encouraged to work in teams.

IEOR E3608x Foundations of optimization 3 pts. Lect: 3. Prerequisite(s): MATH UN2010. Corequisite(s): Data structures. This first course in optimization focuses on theory and applications of linear optimization, network optimization, and dynamic programming.

IEOR E3609y Advanced optimization 3 pts. Lect: 3. Prerequisite(s): IEOR E3608. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This is a follow-up to IEOR E3608 and will cover advanced topics in optimization, including integer optimization, convex optimization, and optimization under uncertainty, with a strong focus on modeling, formulations, and applications.

IEOR E3658x and y Probability for engineers 3 pts. Lect: 3. Prerequisite(s): Calculus. For undergraduates only. Required for OR:FE concentration. Must be taken during or before third semester. Students who take IEOR E3658 may not take W4150 due to significant overlap. Recommended: strong mathematical skills. Introductory course to probability theory and does not assume any prior knowledge of subject. Teaches foundations required to use probability in applications, but course itself is theoretical in nature. Basic definitions and axioms of probability and notions of independence and conditional probability introduced. Focus on random variables, both continuous and discrete, and covers topics of expectation, variance, conditional distributions, conditional expectation and variance, and moment generating functions. Also Central Limit Theorem for sums of random variables. Consists of lectures, recitations, weekly homework, and in-class exams.

IEOR E3900x and y Undergraduate research or project 1–3 pts. Members of the faculty. Prerequisite(s): Approval by a faculty member who agrees to supervise the work. Independent work involving experiments, computer programming, analytical investigation, or engineering design.

IEOR E3999x, y or s Fieldwork 1–1.5 pts. (up to 2 pts., summer only) Prerequisite(s): Obtained internship and approval from faculty adviser. Only for IEOR undergraduate students who need relevant work experience as part of their program of study. Final reports are required. May not be taken for pass/fail credit or audited.

IEOR E4003x Corporate finance for engineers 3 pts. Lect: 3. Prerequisite(s) or corequisites: Probability theory and linear programming. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Introduction to the economic evaluation of industrial projects. Economic equivalence and criteria. Deterministic approaches to economic analysis. Multiple projects and constraints. Analysis and choice under risk and uncertainty.

IEOR E4004x and y Optimization models and methods 3 pts. Lect: 3. A graduate course only for MS&E, IE, and OR students. This is also required for students in the Undergraduate Advanced Track. For students who have not studied linear programming. Some of the main methods used in IEOR applications involving deterministic models: linear programming, the simplex method, nonlinear, integer and dynamic programming.

IEOR E4007x Optimization models and methods for financial engineering 3 pts. Lect: 3. Prerequisite(s): Linear algebra. This graduate course is only for M.S. Program in Financial Engineering students. Linear, quadratic, nonlinear, dynamic, and stochastic programming. Some discrete optimization techniques will also be introduced. The theory underlying the various optimization methods is covered. The emphasis is on modeling and the choice of appropriate optimization methods. Applications from financial engineering are discussed.

IEOR E4008x or y Computational discrete optimization 3 pts. Lect: 3. Prerequisite(s): Linear programming, basic probability theory. Discrete optimization problems. Mathematical techniques and testing strengths and limits in practice on relevant applications. Transportation (travelling salesman and vehicle routing) and matching (online advertisement and school allocation) problems.

IEOR E4009x or y Nonlinear optimization 3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): A course on optimization models and methods (at the level of IEOR E4004) and a course on linear algebra. Unconstrained and constrained nonlinear optimization involving continuous functions. Additionally, fundamental concepts such as optimality conditions and convergence, principle focus on practical optimization methods.
CSOR  E4010y  Graph theory: a combinatorial view
Prerequisite(s): Linear algebra, or instructor’s permission. An introductory course in graph theory with emphasis on its combinatorial aspects. Basic definitions, and some fundamental topics in graph theory and its applications. Topics include trees and forests, graph coloring, connectivity, matching theory and others.

IEOR  E4100x Statistics and simulation
1.5 pts. Lect: 1.5.
Prerequisite(s): Understanding of single- and multivariable calculus. Probability and simulation. Statistics building on knowledge in probability and simulation. Point and interval estimation, hypothesis testing, and regression. A specialized version of IEOR E4150 for MSE and MSBA students who are exempt from the first half of IEOR E4101. Must obtain waiver for E4101.

IEOR  E4101x Probability, statistics and simulation
3 pts. Lect: 3.
Prerequisite(s): Understanding of single- and multivariable calculus. MSE and MSBA students only. Basic probability theory; including independence and conditioning, discrete and continuous random variables, law of large numbers, central limit theorem, and stochastic simulation. Basic statistics, including point and interval estimation, hypothesis testing, and regression; examples from business applications such as inventory management, medical treatments, and finance. A specialized version of IEOR E4150 for MSE and MSBA students.

IEOR  E4102y Stochastic models for MSE
3 pts. Lect: 3.
Prerequisite(s): IEOR E4101. Introduction to stochastic processes and models, with emphasis on applications to engineering and management; random walks, gambler’s ruin problem, Markov chains in both discrete and continuous time, Poisson processes, renewal processes, stopping times, Wald’s equation, binomial lattice model for pricing risky assets, simple option pricing; simulation of simple stochastic processes, Brownian motion, and geometric Brownian motion. A specialized version of IEOR E4106 for MSE students.

IEOR  E4106x and y Stochastic models
3 pts. Lect: 3.
Prerequisite(s): STAT GU4001 or probability theory or IEOR E4150. This graduate course is only for IE and OR students. Also required for students in the Undergraduate Advanced Track. Some of the main stochastic models used in engineering and operations research applications: discrete-time Markov chains, Poisson processes, birth and death processes and other continuous Markov chains, renewal reward processes. Applications: queueing, reliability, inventory, and finance.

IEOR  E4108/DROM  B8108x or y Supply chain analytics
3 pts. Lect: 2.5.
Prerequisite(s): IEOR E3402 or instructor’s permission. MS IEOR students only. Supply chain management, model design of a supply chain network, inventories, stock systems, commonly used inventory models, supply contracts, value of information and information sharing, risk pooling, design for postponement, managing product variety, information technology and supply chain management; international and environmental issues. Note: replaced IEOR E4000 beginning in fall 2019.

IEOR  E4111x and y Operations consulting
3 pts. Lect: 3.
Prerequisite(s): Probability and statistics at the level of IEOR E3658 and E4307 or STAT GU4001, and Deterministic Models at the level of IEOR E3608 or IEOR E4004, or instructor permission. For MS-MSAE students only. Aims to develop and harness the modeling, analytical, and managerial skills of engineering students and apply them to improve the operations of both service and manufacturing firms. Structured as a hands-on laboratory in which students “learn by doing” on real-world consulting projects (October to May). The student teams focus on identifying, modeling, and testing (and sometimes implementing) operational improvements and innovations with high potential to enhance the profitability and/or achieve sustainable competitive advantage for their sponsor companies. The course is targeted toward students planning careers in technical consulting (including operations consulting) and management consulting, or pursuing positions as business analysts in operations, logistics, supply chain and revenue management functions, positions in general management, and future entrepreneurs.

IEOR  E4150x Introduction to probability and statistics
3 pts. Lect: 3.
Prerequisite(s): Calculus, including multiple integration. Covers the following topics: fundamentals of probability theory and statistical inference used in engineering and applied science; Probabilistic models, random variables, useful distributions, expectations, law of large numbers, central limit theorem; Statistical inference: pint and confidence interval estimation, hypothesis tests, linear regression. For IEOR graduate students.

IEOR  E4199y MSIEOR quantitative bootcamp
0 pt. Lect: 0.
Zero-credit course. Primer on quantitative and mathematical concepts. Required for all incoming MSOR and MSIE students.

IEOR  E4200x or y Human-centered design & innovation
3 pts. Lect: 2.5.
Prerequisite(s): Instructor’s permission. Open to SEAS graduate and advanced undergraduate students, Business School, and GSAPP. Students from other schools may apply. Fast-paced introduction to human-centered design. Students learn the vocabulary of design methods, understanding of design process. Small group projects to create prototypes. Design of simple product, more complex systems of products and services, and design of business.

ORCS  E4200y Data-driven decision modeling
3 pts. Lect: 3.
Introduction to modeling, estimating, and solving decision-making problems in the context of artificial intelligence and analytics. Potential topics include choice models, quantity models, online learning using multi-armed bandits, dynamic decision modeling, dynamic games, and Bayesian learning. Practice both theory and applications using Python programming.

IEOR  E4206x or y Intellectual property for engineers
Intellectual property (patents, copyrights, trademarks) are an increasingly critical part of almost any business, at almost any stage of growth. Provides the aspiring business executive, tech entrepreneur, or engineer with an overview of commercial opportunities and risks associated with intellectual property, with a particular focus on technology patents. While legal principles will be addressed, the primary focus is on leveraging intellectual property to create financial returns.

IEOR  E4207x Human factors: performance
3 pts. Lect: 3.
Required for undergraduate students majoring in IE. Sensory and cognitive (brain) processing considerations in the design, development, and operations of systems, products, and tools. User or operator limits and potential in sensing, perceiving decision making, movement coordination, memory, and motivation.

IEOR  E4208y Seminar in human factors design
3 pts. Lect: 3.
Prerequisite(s): IEOR E4207 or instructor’s permission. An elective for undergraduate students majoring in IE. An in-depth exploration of the application potential of human factor principles for the design of products and processes. Applications to industrial products, tools, layouts, workplaces, and computer displays. Consideration to environmental factors, training and documentation. Term project.

IEOR  E4212x Data analytics and machine learning for OR
3 pts. Lect: 3.
Surveys tools available in Python for getting (web scraping and APIs) and visualizing data (charts and maps). Introduction to analytics through machine learning (ML algorithms, model evaluation, text analytics, network algorithms, deep learning).

IEOR  E4307x Statistics and data analysis for OR
3 pts. Lect: 3.
Prerequisite(s): probability, linear algebra. Descriptive statistics, central limit theorem, parameter estimation, sufficient statistics, hypothesis testing, regression, logistic regression, goodness-of-fit tests, applications to operations research models.

IEME  E4310x The manufacturing enterprise
The strategies and technologies of global manufacturing and service enterprises. Connections
between the needs of a global enterprise, the technology and methodology needed for manufacturing and product development, and strategic planning as currently practiced in industry.

**IEOR E4311x Derivatives marketing & structuring**
1.5 pts. Lect: 1.5.
Prerequisite(s): IOR E3402, IOR E4000, or instructor's permission. Covers topics in Accounting, relationships among different elements of financial statements, short-term and long-term financing alternatives, using swaps, cap, and floors to manage interest rate risk, hedging interest risk of corporate finance, using options as cheapers, structured swaps, accounting treatment of derivatives, cash flow hedging, accrual accounting, hedging issuance of a bond using treasuries, hedging employee stock options, preferred shares and their use in corporate treasury, FX risk and FX translation, commodities hedging, operating lease vs capital lease, credit risk, and cred spread and funding. Note: restricted to IOR MS students.

**IEOR E4312y Application of OR & AI techniques in marketing**
1.5 pts. Lect: 1.5.
Prerequisite(s): working knowledge of Excel, high level language (such as Python, R, MATLAB, or VBA), and intro course in probability and statistics. Covers working knowledge of quantitative methods and data mining techniques applied to marketing and customer relationship management. Topics include clustering methods, conjoint analysis and customer preferences, forecasting, market share, product life cycle, new product, nearest neighbor, discriminant analysis, decision tree, revenue management, price and advertising elasticity, resource allocation and return on investment (ROI), economic analysis of a network and its formation, and networked markets. Note: restricted to IOR MS students.

**IEOR E4399y MSE quantitative bootcamp**
0 pt. Lect: 0.
Zero-credit course. Primer on quantitative and mathematical concepts. Required for all incoming MSOR and MSIE students.

**IEOR E4402x Corporate finance, accounting, & investment banking**
3 pts. Lect: 3.
Prerequisite(s): Covers primary financial theories and alternative theories underlying Corporate Finance, such as CAPM, Miller Modigliani, Fama French factors, Smart Beta, etc. Interpret financial statements, build cash flow models, value projects, value companies, and make Corporate Finance decisions. Additional topics include: cost of capital, dividend policy, debt policy, impact of taxes, Shareholder/Debtholder agency costs, dual-class shares, using option pricing theory to analyze management behavior, investment banking activities, including equity underwriting, syndicated lending, venture capital, private equity investing and private equity secondaries. Application of theory in real-world situations: analyzing financial activities of companies such as General Electric, Google, Snapchat, Spotify, and Tesla.

**IEOR E4403x Quantitative corporate finance**
3 pts. Lect: 3.
Prerequisite(s): Probability theory and linear programming Required for students in the Undergraduate Advanced Track. Key measures and analytical tools to assess the financial performance of a firm and perform the economic evaluation of industrial projects. Deterministic mathematical programming models for capital budgeting. Concepts in utility theory, game theory and real options analysis.

**IEOR E4404x and y Simulation**
Prerequisite(s): IOR E3658 and E4307 or STAT GU4001, computer programming. Corequisite(s): IOR E3106 or IOR E4106. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Also required for MSOR. Generation of random numbers from given distributions; variance reduction; statistical output analysis; introduction to simulation languages; application to financial, telecommunications, computer, and production systems. Graduate students must register for 3 points. Undergraduate students must register for 4 points. Note: Students who have taken IOR E4703 Monte Carlo simulation may not register for this course for credit. Recitation section required.

**IEOR E4405y Scheduling**
3 pts. Lect: 3.

**IEOR E4407x Game theoretic models of operations**
3 pts. Lect: 3.
Prerequisite(s): IOR E4004 (or E3608), IOR E4106 (or E3106), familiarity with differential equations and computer programming; or instructor’s permission. Required for undergraduate students majoring in OR:FE and OR. A mathematically rigorous study of game theory and auctions, and their application to operations management. Topics include introductory game theory, private value auction, revenue equivalence, mechanism design, optimal auction, multiple-unit auctions, combinatorial auctions, incentives, and supply chain coordination with contracts. No previous knowledge of game theory is required.

**IEOR E4408x Resource allocation: models, algorithms, and applications**
Prerequisite(s): Linear programming (IEOR E3608 or E4004), basic knowledge of nonlinear and integer programming. Overview of resource allocation models. Single resource allocation with concave returns; equitable resource allocation; lexicographic minmax/maxmin optimization; extensions to substitutable resources; multiperiod resource allocation; equitable allocation in multicommodity network flow models; equitable content distribution in networks; equitable resource allocation with discrete decision variables.

**IEOR E4412y Quality control and management**
3 pts. Lect: 3.
Prerequisite(s): IOR E3658 and working knowledge of statistics. Required for undergraduate students majoring in IE. Statistical methods for quality control and improvement; graphical methods, introduction to experimental design and reliability engineering and the relationships between quality and productivity. Contemporary methods used by manufacturing and service organizations in process and product design, production and delivery of products and services.

**IEOR E4418x or y Transportation analytics and logistics**
3 pts. Lect: 3.
Prerequisite(s): IOR E3608 or E4404 or permission of instructor. Introduces quantitative techniques and state-of-the-art practice of operations research relevant to the design and both the tactical and strategic management of logistical and transportation systems. Discusses a wide variety of passenger and freight systems, including air, urban and highway traffic, rail, and maritime systems. Explores the practice of revenue management and dynamic pricing. Through case studies, analyzes successes and failures in third-party logistics, postal, truck and rail pickup and delivery systems. Investigates large-scale integrated logistics and transportation systems and studies the underlying principles governing transportation planning, investment and operations.

**IEOR E4500x Applications programming for financial engineering**
3 pts. Lect: 3.
Prerequisite(s): Computer programming or instructor’s approval. Required for undergraduate students majoring in OR:FE. We will take a hands-on approach to developing computer applications for Financial Engineering. Special focus will be placed on high-performance numerical applications that interact with a graphical interface. In the course of developing such applications we will learn how to create DLLs, how to integrate VBA with C/C++ programs, and how to write multithreaded programs. Examples of problems settings that we consider include simulation of stock price evolution, tracking, evaluation and optimization of a stock portfolio; optimal trade execution. In the course of developing these applications, we review topics of interest to OR:FE in a holistic fashion.

**ORCA E4500x or y Foundations of data science**
3 pts. Lect: 3.
Prerequisite(s): MATH UN1101 and UN1102, some familiarity with programming. Designed to provide an introduction to data science for sophomore and SEAS majors. Combines three perspectives: inferential thinking, computational thinking, and real-world applications. Given data arising from some real-world phenomenon, how does one analyze that data so as to understand that phenomenon? Teaches critical concepts and skills in computer programming, statistical inference, and machine learning, in conjunction with hands-on analysis of real-world datasets such as economic data,
document collections, geographical data, and social networks.

**IEOR E4501x and y Tools for analytics**  
3 pts. Lect: 3.  
MS IEOR students only. Introduction programming in Python, tools with the programmer's ecosystem. Python, Data Analysis tools in Python (NumPy, pandas, bokeh), Git, Bash, SQL, VIM, Linux/Debian, SSH.

**IEOR E4502x Python for analytics**  
0 pts. Lect: 1.  
Zero-credit course. Primer on Python for analytics concepts. Required for MSBA students.

**IEOR E4505y Operations research in public policy**  
3 pts. Lect: 3.  
Prerequisite(s): IEOR E3608 or IEOR E4004, IEOR E3106 or IEOR E4106. Aims to give the student a broad overview of the role of Operations Research in public policy. The specific areas covered include voting theory, apportionment, deployment of emergency units, location of hazardous facilities, health care, organ allocation, management of natural resources, energy policy, and aviation security. Draws on a variety techniques such as linear and integer programming, statistical and probabilistic methods, decision analysis, risk analysis, and analysis and control of dynamic systems.

**IEOR E4506x Designing digital operating models**  
3 pts. Lect: 3.  

**IEOR E4507x or y Healthcare operations management**  
3 pts. Lect: 3.  
Prerequisite(s): for senior undergraduate Engineering students: IEOR E3608, E3658, and E4307; for Engineering graduate students (M.S. or Ph.D.): Probability and statistics at the level of IEOR E4150, and deterministic models at the level of IEOR E4004; for healthcare management students: HPNM P5829 Analytical methods for health services management. Develops modeling, analytical, and managerial skills of engineering and health care management students. Enables students to master an array of fundamental operations management tools adapted to the management of health care systems. Through real-world business cases, students learn to identify, model, and analyze operational improvements and innovations in a range of health care contexts.

**IEOR E4510y Project management**  
3 pts. Lect: 3.  
Prerequisite(s): IEOR E4004 or IEOR E3608. Management of complex projects and the tools that are available to assist managers with such projects. Topics include project selection, project teams and organizational issues, project monitoring and control, project risk management, project resource management, and managing multiple projects.

**IEOR E4511x or y Industry projects in analytics and operations research**  
3 pts. Lect: 3.  
Teams of students work on real-world projects in analytics. Focus on three aspects of analytics: identifying client analytical requirements; assembling, cleaning and organizing data; identifying and implementing analytical techniques (e.g., statistics and/or machine learning); and delivering results in a client-friendly format. Each project has a defined goal and pre-identified data to analyze in one semester. Client facing class. Class requires 10 hours of time per week and possible client visits on Fridays.

**IEOR E4520x Applied systems engineering**  
3 pts. Lect: 3.  
Prerequisite(s): B.S. in engineering or applied sciences; professional experience recommended; calculus, probability and statistics, linear algebra. Introduction to fundamental methods used in systems engineering. Rigorous process that translates customer needs into a structured set of specific requirements; synthesizes a system architecture that satisfies those requirements and allocates them in a physical system, meeting cost, schedule, and performance objectives throughout the product life-cycle. Sophisticated modeling of requirements optimization and dependencies, risk management, probabilistic scenario scheduling, verification matrices, and systems-of-systems constructs are synthesized to define the meta-workflow at the top of every major engineering project.

**IEOR E4521y Systems engineering tools and methods**  
3 pts. Lect: 3.  
Prerequisite(s): B.S. in engineering or applied sciences; probability and statistics, optimization, linear algebra, and basic economics. Applications of SE tools and methods in various settings. Encompasses modern complex system development environments, including aerospace and defense, transportation, energy, communications, and modern software-intensive systems.

**IEOR E4523x and y Data analytics**  
3 pts. Lect: 3.  
Corequisite(s): IEOR E4522 or E4501. IEOR students only; priority to MSBA students. Survey tools available in Python for getting, cleaning, and analyzing data. Obtain data from files (csv, html, json, xml) and databases (Mysql, PostgreSQL, NoSQL), cover the rudiments of data cleaning, and examine data analysis, machine learning, and data visualization packages (NumPy, pandas, Scikit-learn, bokeh) available in Python. Brief overview of natural language processing, network analysis, and big data tools available in Python. Contains a group project component that will require students to gather, store, and analyze a data set of their choosing.

**IEOR E4524y Analytics in practice**  
3 pts. Lect: 3.  
Prerequisite(s): IEOR E4522 or E4501 and IEOR E4523. Groups of students will work on real-world projects in analytics, focusing on three aspects: identifying client analytical requirements; assembling, cleaning, and organizing data; identifying and implementing analytical techniques (statistics, OR, machine learning); and delivering results in a client-friendly format. Each project has a well-defined goal, comes with sources of data preidentified, and has been structured so that it can be completed in one semester. Client-facing class with numerous on-site client visits; students should keep Fridays clear for this purpose.

**IEOR E4525y Machine learning for financial engineering and operations research**  
3 pts. Lect: 3.  
Prerequisite(s): Optimization, applied probability, statistics, and knowledge of (or experience in) computer programming. MS IEOR students only. Introduction to machine learning, practical use of ML algorithms and applications to financial engineering and operations. Supervised learning: regression, classification, resampling methods, regularization, support vector machines (SVMs), and deep learning. Unsupervised learning: dimensionality reduction, matrix decomposition, and clustering algorithms.

**IEOR E4526x or y Analytics on the cloud**  
3 pts. Lect: 3.  
Prerequisite(s): IEOR E4501 and E4523. To introduce students to programming issues around working with clouds for data analytics. Class will learn how to work with infrastructure of cloud platforms, and discussion about distributed computing, focus of course is on programming. Topics covered include MapReduce, parallelism, rewriting of algorithms (statistical, OR, and machine learning) for the cloud, and basics of porting applications so that they run on the cloud.

**ORCS E4529y Reinforcement learning**  
3 pts. Lect: 3. Professor Agrawal.  
Prerequisite(s): Probability and statistics, basic optimization (e.g., familiarity with linear and convex optimization, gradient descent, basic algorithm design constructs), familiarity with programming in Python. Markov Decision Processes (MDP) and Reinforcement Learning (RL) problems. Reinforcement Learning algorithms including Q-learning, policy gradient methods, actor-critic method. Reinforcement learning while doing exploration-exploitation dilemma, multi-armed bandit problem. Monte Carlo Tree Search methods; Distributional, Multi-agent, and Causal Reinforcement Learning.

**IEOR E4532x and y Data visualization**  
1.5 pts. Lect: 1.5.  
Data visualization and how to build a story with data. Using complex data or statistics to communicate results effectively. Learn to present analysis results coherently and effectively.

**IEOR E4533x and y Performance, objectives, and results using analytics**  
1.5 pts. Lect: 1.5.  
OKR framework and different variations.
IEOR E4540x and y Data mining for engineers 3 pts. Lect: 3. Prerequisite(s): Linear Algebra, Calculus, Probability, and some basic programming. Course covers major statistical learning methods for data mining under both supervised and unsupervised settings. Topics covered include linear regression and classification, model selection and regularization, tree-based methods, support vector machines, and unsupervised learning. Students learn about principles underlying each method, how to determine which methods are most suited to applied settings, concepts behind model fitting and parameter tuning, and how to apply methods in practice and assess their performance. Emphasizes roles of statistical modeling and optimization in data mining.

IEOR E4550x Entrepreneurial business creation for engineers 3 pts. Lect: 3. Prerequisite(s): IEOR E2261. Required for undergraduate students majoring in OR:EMS. Introduces the basic concepts and methodologies that are used by the nonengineering part of the world in creating, funding, investing in, relating to, and operating entrepreneurial ventures. The first half of the course focuses on the underpinning principles and skills required in recognizing, analyzing, evaluating, and nurturing a business idea. The second half focuses on basic legal knowledge necessary in creating a business entity, defending your business assets, and in promoting effective interaction with other individuals and organizations.

IEOR E4555x or y Design and agile project management engineering lab 3 pts. Lect: 3. Not offered in 2022–2023. Intensive, team-, and project-based seminar covering multidisciplinary approach to evidence-based product design; agile project planning and execution; rapid MVP prototyping; and launch strategy formulation and implementation. Focuses on practical use of design thinking, design studio, and iterative design sprint methodologies. Systematic approaches to Lean User Research, User Experience (UX), and User Interface (UI) design and deployment are integral components of course curriculum. Mix of startup and enterprise projects, including application drive, data-driven, or combination of both. Teams are fully supported in devising prototypes and actualizing proposed solutions.

IEOR E4561x or y Launch your startup: tech 3 pts. Lect: 3. Tools and knowledge to develop a comprehensive new venture that is scalable, repeatable, and capital efficient. Covers customer discovery, market sizing, pricing, competition, distribution, funding, developing a minimal viable product, and other facets of creating new ventures. A company blueprint and final investor pitch are deliverables.

IEOR E4562x, y, or z Innovate using design thinking 3 pts. Lect: 3. How Design Thinking can enhance innovation activities, market impact, value creation, and speed. Topics include: conceptual and practical understanding of design thinking, creative solutions, develop robust practices to lead interdisciplinary teams. Course aims to strengthen individual and collaborative capabilities to identify customer needs, indirect and qualitative research, create concept hypotheses, develop prototype, defined opportunities into actionable innovation possibilities, and recommendations for client organizations.

IEOR E4562x and y Technology breakthroughs 1.5 pts. Lect: 1.5 Technology breakthroughs driven change, disruption, and transformation of the business landscape/society. Course covers overview of deep learning and neural networks; AI and robotics; imaging and vision; photonics; blockchain; smart/digital cities; and the application of these technologies for creating new products and services.

IEOR E4570-4579x and y Topics in operations research 1.5–3 pts. Lect: 1.5–2. Members of the faculty. Prerequisite(s): IEOR E4150, E4004, and E4106, or instructor’s permission. Each offering of this course is devoted to a particular sector of Operations Research and its contemporary research, practice, and approaches. If topics are different, then course can be taken more than once for credit.

IEOR E4599x MSBA quantitative bootcamp 0 pts. Lect: 3. Primer on quantitative and mathematical concepts. Required for all incoming MSBA students.

IEOR E4601y Dynamic pricing and revenue management 3 pts. Lect: 3. Prerequisite(s): STAT GU4001 and IEOR E4106. Focus on capacity allocation, dynamic pricing and revenue management. Perishable and/or limited product and pricing implications. Applications to various industries including service, airlines, hotels, resource rentals, etc.

IEOR E4602y Quantitative risk management 3 pts. Lect: 3. Prerequisite(s): STAT GU4001 and IEOR E4106. Risk management models and tools; measure risk using statistical and stochastic methods, hedging and diversification. Examples include insurance risk, financial risk, and operational risk. Topics covered include VaR, estimating rare events, extreme value analysis, time series estimation of extremal events; axioms of risk measures, hedging using financial options, credit risk modeling, and various insurance risk models.

IEOR E4615y Service engineering 3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): Introductory courses in probability and statistics such as IEOR E3658 and E4307, and introductory courses in stochastic processes such as IEOR E3106 or IEOR E4106. Focus on service systems viewed as stochastic networks, exploiting the theoretical framework of queueing theory. Includes multidisciplinary perspectives involving Statistics, Psychology, and Marketing. Significant emphasis on data analysis, exploiting data from banks, hospitals, and call centers to demonstrate the use of decision support tools. Analytical models, flow models of service networks, Little’s law, measuring methods in face-to-face and computerized systems, forecasting methods, stability of service systems, operational quality of service, economies of scale, staffing, complex service networks, skill-based routing.

IEOR E4620x Pricing models for financial engineering 3 pts. Lect: 3. Prerequisite(s): IEOR E4700. Required for undergraduate students majoring in OR:FE. Characteristics of commodities or credit derivatives. Case study and pricing of structures and products. Topics covered include swaps, credit derivatives, single tranche CDO, hedging, convertible arbitrage, FX, leverage leases, debt markets, and commodities.

IEOR E4630y Asset allocation 3 pts. Lect: 3. Prerequisite(s): IEOR E4700. Models for pricing and hedging equity, fixed-income, credit-derivative securities, standard tools for hedging and risk management, models and theoretical foundations for pricing equity options (standard European, American equity options, Asian options), standard Black-Scholes model (with multiasset extension), asset allocation, portfolio optimization, investments over lifetime horizons, and pricing of fixed-income derivatives (Ho-Lee, Black-Derman-Toy, Heath-Jarrow-Morton interest rate model).

IEOR E4650x and y Business analytics 3 pts. Lect 3. Recit: 1. Prerequisite(s): STAT GU4001 or IEOR E4150. Prepares students to gather, describe, and analyze data, using advanced statistical tools to support operations, risk management, and response to disruptions. Analysis is done by targeting economic and financial decisions in complex systems that involve multiple partners. Topics include probability, statistics, hypothesis testing, experimentation, and forecasting.

IEOR E4700x and y Introduction to financial engineering 3 pts. Lect: 3. Prerequisite(s): IEOR E4106 or E3106. Required for undergraduate students majoring in OR:FE. Introduction to investment and financial instruments and asset pricing theory. Course covers the basic operations research/engineering methodology. Portfolio theory, arbitrage; Markowitz model, market equilibrium, and the capital asset pricing model. General models for asset price fluctuations in discrete and continuous time. Elementary introduction to Brownian motion and geometric Brownian motion. Option theory; Black-Scholes equation and call option formula. Computational methods such as Monte Carlo simulation.
IEOR E4701x Stochastic models for financial engineering
3 pts. Lect: 3.
Prerequisite(s): STAT GU4001. This graduate course is only for M.S. Program in Financial Engineering students, offered during the summer session. Review of elements of probability theory, Poisson processes, exponential distribution, renewal theory, Wald’s equation. Introduction to discrete-time Markov chains and applications to queueing theory, inventory models, branching processes.

IEOR E4703y Monte Carlo simulation
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701. This graduate course is only for M.S. Program in Financial Engineering students. Multivariate random number generation, bootstrapping, Monte Carlo simulation, efficiency improvement techniques. Simulation output analysis, Markov-chain Monte Carlo. Applications to financial engineering. Introduction to financial engineering simulation software and exposure to modeling with real financial data. Note: Students who have taken IEOR E4404 Simulation may not register for this course for credit.

IEOR E4706x Foundations of financial engineering
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701, E4702, and linear algebra. This graduate course is only for M.S. Program in Financial Engineering students, offered during the summer session. Discrete-time models of equity, bond, credit, and foreign-exchange markets. Introduction to derivative markets. Pricing and hedging of derivative securities. Complete and incomplete markets. Introduction to portfolio optimization and the capital asset pricing model.

IEOR E4707y Financial engineering: continuous-time asset pricing
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701. This graduate course is only for M.S program in FE students. Modeling, analysis, and computation of derivative securities. Applications of stochastic calculus and stochastic differential equations. Numerical techniques: finite-difference, binomial method, and Monte Carlo.

IEOR E4708y Seminar on important papers in financial engineering
Prerequisite(s): IEOR E4703, E4706, probability and statistics. Selected topics of special interest to M.S. students in financial engineering. If topics are different then this course can be taken more than once for credit.

IEOR E4709y Statistical analysis and time series
3 pts. Lect: 3.
Prerequisite(s): Probability and IEOR E4702. Corequisite(s): IEOR E4706, E4707. This graduate course is only for M.S. Program in Financial Engineering students. Empirical analysis of asset prices: heavy tails, test of the predictability of stock returns. Financial time series: ARMA, stochastic volatility, and GARCH models. Regression models: linear regression and test of CAPM, non-linear regression and fitting of term structures.

IEOR E4710x Fixed income and term structure modeling
Prerequisite(s): IEOR E4706, E4707, and computer programming. Interest rate models and numerical techniques for pricing and hedging interest rate contracts and fixed income securities.

IEOR E4711x Global capital markets
3 pts. Lect: 3.
Prerequisite(s): Refer to course syllabus. An introduction to capital markets and investments providing an overview of financial markets and tools for asset valuation. Topics covered include the pricing of fixed-income securities (treasury markets, interest rate swaps futures, etc.), discussions on topics in credit, foreign exchange, sovereign ad securitized markets—private equity and hedge funds, etc.

IEOR E4712x Behavioral finance
Prerequisite(s): IEOR E4700. Behavioral finance is the application of behavioral psychology to financial decision making. Focuses on the portfolio aspect of behavioral finance and briefly touches on other aspects. Compared with classical theory of portfolio choice, behavioral portfolio choice features human being’s psychological biases. It builds both on behavioral preference structures different from mean variance theory and expected utility theory and on systematic biases against rational beliefs such as Bayesian rule.

IEOR E4714x Risk management, financial system and financial crisis
Prerequisite(s): IEOR E4700. Risk-taking and risk management are at the heart of the financial system, and of the current financial crisis. An introduction to risk management both from an individual financial firm’s and from a public policy viewpoint. Overview of the contemporary financial system, focusing on innovations of the past few decades that have changed how financial risk is generated and distributed among market participants, such as the growth of non-bank financial intermediaries, the increased prevalence of leverage and liquidity risk, and the development of structured credit products. Introduction to the basic quantitative tools used in market, credit, and liquidity risk management. The two strands of the course are brought together to help understand how the financial crisis arose and is playing out, examining the mechanics of runs and the behavior of asset prices during crises. Attempt to understand the emergency programs deployed by central bankers and other policy makers to address crises historically and today.

IEOR E4715x, s Commodity derivatives
Prerequisite(s): IEOR E4706, E4707. Commodities markets have been much in the public eye recently as volatility has increased and they changed from markets dominated by physical participants to ones which have a significant investor component. The largest banks either already have profitable commodities franchises or are actively building them, and money managers and funds are increasingly including these assets in their portfolio mix. The end result is a dramatic increase in focus on these markets from all aspects of the financial markets, including the quantitative end.

IEOR E4718x or y Beyond Black-Scholes: the implied volatility smile
3 pts. Lect: 3.
Prerequisite(s): IEOR E4706, knowledge of derivatives valuation models. During the past 15 years the behavior of market options prices have shown systematic deviations from the classic Black-Scholes model. Examines the empirical behavior of implied volatilities, in particular the volatility smile that now characterizes most markets, the mathematics and intuition behind new models that can account for the smile, and their consequences for hedging and valuation.

IEOR E4720–E4729 x and y Topics in quantitative finance
1.5–3 pts. Lect: 2–2.5. Members of the faculty.
Prerequisite(s): IEOR E4700; additional Prerequisite(s) will be announced depending on offering. Selected topics of interest in the area of quantitative finance. Offerings vary each year; some topics include energy derivatives, experimental finance, foreign exchange and related derivative instruments, inflation derivatives, hedge fund management, modeling equity derivatives in Java, mortgage-backed securities, numerical solutions of partial differential equations, quantitative portfolio management, risk management, trade and technology in financial markets.

IEOR E4731x Credit risk modeling and derivatives
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701 and E4707. Introduction to quantitative modeling of credit risk, with a focus on the pricing of credit derivatives. Focus on the pricing of single-name credit derivatives (credit default swaps) and collateralized debt obligations (CDOs). Detailed topics include default and credit risk, multivariate default barrier models and multivariate reduced form models.

IEOR E4732x Computational methods in finance
3 pts. Lect: 3.
Prerequisite(s): IEOR E4700. MS IEOR students only. Application of various computational methods/techniques in quantitative/computational finance. Transform techniques: fast Fourier transform for data de-noising and pricing, finite difference methods for partial differential equations (PDE), partial integro-differential equations (PIDE), Monte-Carlo simulation techniques in finance, and calibration techniques, filtering and parameter estimation techniques. Computational platform will be C+/Java/Python/Matlab/R.

IEOR E4733x or y Algorithmic trading
Prerequisite(s): IEOR E4700. Large and amorphous collection of subjects ranging from the study of market microstructure, to the analysis of optimal trading strategies, to the development of computerized, high-frequency trading strategies. Analysis of these subjects, the scientific and practical issues they involve, and the extensive
body of academic literature they have spawned. Attempt to understand and uncover the economic and financial mechanisms that drive and ultimately relate them.

**IEOR E4734y Foreign exchange and related derivatives instruments**
3 pts. Lect: 1.5. Prerequisite(s): IEOR E4700. Foreign exchange market and its related derivative instruments—the latter being forward contracts, futures, options, and exotic options. What is unusual about foreign exchange is that although it can rightfully claim to be the largest of all financial markets, it remains an area where very few have any meaningful experience. Virtually everyone has traded stocks, bonds, and mutual funds. Comparatively few individuals have ever traded foreign exchange. In part that is because foreign exchange is an interbank market. Ironically the foreign exchange markets may be the best place to trade derivatives and to invent new derivatives—given the massive two-way flow of trading that goes through bank dealing rooms virtually 24 hours a day. And most of that is transacted at razor-thin margins, at least comparatively speaking, a fact that makes the foreign exchange market an ideal platform for derivatives. The emphasis is on familiarizing the student with the nature of the foreign exchange market and those factors that make it special among financial markets, enabling the student to gain a deeper understanding of the related market for derivatives on foreign exchange.

**IEOR E4735y Structured and hybrid products**
3 pts. Lect: 3. Prerequisite(s): IEOR E4700. Conceptual and practical understanding of structured and hybrid products from the standpoint of relevant risk factors, design goals and characteristics, pricing, hedging, and risk management. Detailed analysis of the underlying cash-flows, embedded derivative instruments, and various structural features of these transactions, both from the investor and issuer perspectives, and analysis of the impact of the prevailing market conditions and parameters on their pricing and risk characteristics. Numerical methods for valuing and managing risk of structured/hybrid products and their embedded derivatives and their application to equity, interest rates, commodities and currencies, inflation, and credit-related products. Conceptual and mathematical principles underlying these techniques, and practical issues that arise in their implementations in the Microsoft Excel/VBA and other programming environments. Special contractual provisions encountered in structured and hybrid transactions, and incorporation of yield curves, volatility smile, and other features of the underlying processes into pricing and implementation framework for these products.

**IEOR E4738x Programming for FE 1: tools for building financial data and risk systems**
3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): Familiarity with object-oriented programming. Object-oriented programming and database development for building financial data and risk systems; Python and Python’s scientific libraries; basic database theory, querying and constructing databases; basic risk management and design of risk systems.

**IEOR E4739y Programming for FE 2: implementing high-performance financial systems**
3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): IEOR E4738 and instructor’s permission. Developing effective software implementations in C programming language; modeling of portfolio optimization; modeling of price impact trading models; review of synchronization of programs using the file system; review of synchronization of programs using threads; review of synchronization of programs using sockets; implementation of high-performance simulations in finance.

**IEOR E4741x Programming for Financial Engineering**
3 pts. Lect: 3. Covers C++ programming language, applications, and features for financial engineering, and quantitative finance applications. Note: restricted to IEOR MS FE students only.

**IEOR E4742x and y Deep learning and its applications in FE and OR**
3 pts. Lect: 3. Selected topics of interest in area of quantitative finance. Some topics include energy derivatives, experimental finance, foreign exchange and related derivative instruments, inflation derivatives in Java, mortgage-backed securities, numerical solutions of partial differential equations, quantitative portfolio management, risk management, trade and technology in financial markets. Note: open to IEOR students only.

**IEOR E4743s Financial correlations—modeling, trading, risk management & AI**
3 pts. Lect: 3. Introduction to math finance, knowledge of working as a “Quant” in investment banking, hedge funds, algo shop, HFT firm, Fed, Exchange, SEC, IMF, back office, mutual fund, as a trader in risk management, product development, model validation, compliance, reporting, academia. Open only to master’s students in IEOR department.

**IEOR E4744s Financial correlations—modeling, trading, risk management & AI**
3 pts. Lect: 3. Introduction to math finance, knowledge of working as a “Quant” in investment banking, hedge funds, algo shop, HFT firm, Fed, Exchange, SEC, IMF, back office, mutual fund, as a trader in risk management, product development, model validation, compliance, reporting, academia. Open only to master’s students in IEOR department.

**IEOR E4745x Applied financial risk management**
3 pts. Lect: 3. Prerequisite(s): courses in probability and statistics, instruments of the financial markets, and asset pricing models. Introduces risk management principles, practical implementation and applications, standard market, liquidity, and credit risk measurement techniques, and their drawbacks and limitations. Note: restricted to IEOR students only.

**IEOR E4798x Financial Engineering practitioners seminar series**

**IEOR E4799x MSFE quantitative and computational bootcamp**
0 pts. Lect: 3. Primer on quantitative and mathematical concepts. Required of all incoming MSFE students.

**IEOR E4900s, x and y Master’s research or project**
1–3 pts. Members of the faculty. Prerequisite(s): Approval by a faculty member who agrees to supervise the work. Independent work involving experiments, computer programming, analytical investigation, or engineering design.

**IEOR E4998y Managing technological innovation and entrepreneurship**
3 pts. Lect: 3. A required course for undergraduate students majoring in OR:EMS. Focus on the management and consequences of technology-based innovation. Explores how new industries are created, how existing industries can be transformed by new technologies, the linkages between technological development and the creation of wealth and the management challenges of pursuing strategic innovation.

**IEOR E4999s, x and y Fieldwork**
1–1.5 pts (up to 2 pts, summer only). Prerequisite(s): Obtained internship and approval from faculty adviser. Only for IEOR graduate students who need relevant work experience as part of their program of study. Final reports required. May not be taken for pass/fail credit or audited.

**MSIE W6408y Inventory theory**

**IEOR E6602y Nonlinear and convex programming**
for constrained problems. Introduction to nondifferentiable optimization and bundle methods.

**IEOR E6613x Optimization, I**
4.5 pts. Lect: 3.
Prerequisite(s): Linear algebra. Theory and geometry of linear programming. The simplex method. Duality theory, sensitivity analysis, column generation and decomposition. Interior point methods. Introduction to nonlinear optimization: convexity, optimality conditions, steepest descent, and Newton’s method, active set, and barrier methods.

**IEOR E6614y Optimization, II**
4.5 pts. Lect: 3.

**IEOR E6617x Machine learning and high-dimensional data analysis in operations research**
3 pts. Lect: 3.
Discusses recent advances in fields of machine learning: kernel methods, neural networks (various generative adversarial net architectures), and reinforcement learning (with applications in robotics). Quasi Monte Carlo methods in the context of approximating RBF kernels via orthogonal transforms (instances of the structured technique). Will discuss techniques such as TD(0), TD(λ), LSTDQ, LSPI, DQN.

**IEOR E6703y Advanced financial engineering**

**IEOR E6711x Stochastic models, I**
4.5 pts. Lect: 3.
Prerequisite(s): STAT GU4001 or equivalent. Advanced treatment of stochastic modeling in the context of queueing, reliability, manufacturing, insurance risk, financial engineering and other engineering applications. Review of elements of probability theory; exponential distribution; renewal theory; Wald’s equation; Poisson processes. Introduction to both discrete and continuous-time Markov chains; introduction to Brownian motion.

**IEOR E6712y Stochastic models, II**
4.5 pts. Lect: 3.
Prerequisite(s): IEOR E6711 or equivalent. Continuation of IEOR E6711, covering further topics in stochastic modeling in the context of queueing, reliability, manufacturing, insurance risk, financial engineering, and other engineering applications. Topics from among generalized semi-Markov processes; processes with a non-discrete state space; point processes; stochastic comparisons; martingales; introduction to stochastic calculus.

**IEOR E8100x and y Advanced topics in IEOR**
1–3 pts. Members of the faculty.
Prerequisite(s): Faculty adviser’s permission. Selected topics of current research interest. May be taken more than once for credit.

**IEOR E9101s, x and y Research**
1–6 pts. Members of the faculty.
Before registering, the student must submit an outline of the proposed work for approval by the supervisor and the chair of the Department. Advanced study in a specialized field under the supervision of a member of the department staff. May be repeated for credit.
MATERIALS SCIENCE AND ENGINEERING PROGRAM

Program in the Department of Applied Physics and Applied Mathematics, sharing teaching and research with the faculty of the Henry Krumb School of Mines.

200 S. W. Mudd, MC 4701  
212-854-4457  
apam.columbia.edu  
matsci.apam.columbia.edu

M aterials Science and Engineering (MSE) focuses on understanding, designing, and producing technology-enabling materials by analyzing the relationships among the synthesis and processing of materials, their properties, and their detailed structure. This includes a wide range of materials such as metals, polymers, ceramics, and semiconductors. Solid-state science and engineering focuses on understanding and modifying the properties of solids from the viewpoint of the fundamental physics of the atomic and electronic structure.

The undergraduate and graduate programs in materials science and engineering are coordinated through the MSE Program in the Department of Applied Physics and Applied Mathematics. This program promotes the interdepartmental nature of the discipline and involves the Departments of Applied Physics and Applied Mathematics, Chemical Engineering and Applied Chemistry, Electrical Engineering, and Earth and Environmental Engineering in the Henry Krumb School of Mines (HKSM) with advisory input from the Departments of Chemistry and Physics.

Students interested in materials science and engineering enroll in the materials science and engineering program in the Department of Applied Physics and Applied Mathematics. Those interested in the solid-state science and engineering specialty enroll in the doctoral program within Applied Physics and Applied Mathematics or Electrical Engineering. The faculty listed above constitute but a small fraction of those participating in materials research.

Materials science and engineering uses optical, electron, and scanning probe microscopy and diffraction techniques to reveal details of structure, ranging from the atomic to the macroscopic scale—details essential to understanding the relationship between materials synthesis and processing and materials properties, including electronic, magnetic, mechanical, optical, and thermal properties. These studies also give insight into problems of the deterioration of materials in service, enabling designers to prolong the useful life of their products. Materials science and engineering also focuses on new ways to synthesize and process materials, from bulk samples to ultrathin films to epitaxial heterostructures to nanocrystals. This involves techniques such as UHV sputtering; molecular beam epitaxy; plasma etching; laser ablation, chemistry, and recrystallization; and other nonequilibrium processes. The widespread use of new materials and the new uses of existing materials in electronics, communications, and computers have intensified the demand for a systematic approach to the problem of relating properties to structure and have necessitated a multidisciplinary approach.

Materials science and solid-state science use techniques such as transport measurements, X-ray photoelectron spectroscopy, ferromagnetic resonance, inelastic light scattering, luminescence, and nonlinear optics to understand electrical, optical, and magnetic properties on a quantum mechanical level. Such methods are used to investigate exciting new types of structures, such as epitaxial metals, two-dimensional transition metal dichalcogenides, superconductors, and semiconductor surfaces and nanocrystals.

Current Research Activities

Current research activities in the materials science and engineering program at Columbia focus on thin films, electronic and magnetic materials, materials at high pressures, materials for advanced batteries, and the structure of materials. Specific topics under investigation include interfaces, stresses, and grain boundaries in thin films; lattice defects and electrical properties of metals and semiconductors; laser processing and ultrarapid solidification of thin films; nucleation in condensed systems; magnetic and electrical properties of semiconductors and metals; synthesis of nanocrystals.
two-dimensional materials, and nanotechnology-related materials; deposition, in situ characterization, electronic testing, and ultrafast spectroscopy of magnetoelectronic ultrathin films and heterostructures. In addition, there is research in first-principles electronic structure computation.

The research activities in solid-state science and engineering are described later in this section.

LABORATORY FACILITIES
Facilities exist within the Materials Science Laboratory, which also serves as shared facilities for Materials Structural and Mechanical Characterization. Facilities and research opportunities also exist within the inter-departmental Columbia Nanotechnology Initiative (CNI). Modern clean room facilities with optical and e-beam lithography, thin film deposition, and surface analytical probes (STM, SPM, XPS) as well as electron microscopes (SEM, S/TEM) are available. More specialized equipment exists in individual research groups in solid-state engineering and materials science and engineering. The research facilities in solid-state science and engineering are listed in the sections for each host department.

UNDERGRADUATE PROGRAM IN MATERIALS SCIENCE
The objectives of the undergraduate program in the Materials Science Program of the Department of Applied Physics and Applied Mathematics are as follows:

1. Professional employment in industry, including materials production, automotive, aerospace, microelectronics, information storage, medical devices, energy production, storage and conversion, and in engineering consulting firms.
2. Graduate studies in materials science and engineering or related fields.

The undergraduate curriculum is designed to provide the basis for developing, improving, and understanding materials and processes for application in engineered systems. It draws from physics, chemistry and other disciplines to provide a coherent background for immediate application in engineering or for subsequent advanced study. The emphasis is on fundamentals relating atomic-to-microscopic-scale phenomena to materials properties and processing, including design and control of industrially important materials processes. Core courses and electives combine rigor with flexibility and provide opportunities for focusing on such areas as nanomaterials, materials for green energy, materials for infrastructure and manufacturing, materials for health and biotechnology, and materials for next generation electronics.

The unifying theme of understanding and interrelating materials synthesis, processing, structure, and properties forms the basis of our program and is evident in the undergraduate curriculum and in faculty research activities. These activities include work on polycrystalline silicon for flat panel displays; semiconductors for lasers and solar cell applications, magnetic heterostructures for information storage and novel computation architectures; electronic ceramics for batteries, gas sensors and fuel cells; electrodeposition and corrosion of metals; and the analysis and design of high-temperature reactors and first principles calculations. Through involvement with our research groups, students gain valuable hands-on experience and are often engaged in joint projects with industrial and government laboratories.

Students are strongly encouraged to take courses in the order specified in the course tables; implications of deviations should be discussed with a departmental adviser before registration. The first two years provide a strong grounding in the physical and chemical sciences, materials fundamentals, and mathematics. This background is used to provide a unique physical approach to the study of materials. The last two years of the undergraduate program provide substantial exposure to modern materials science and include courses in processing, structure and properties of materials that extend the work of the first two years. Graduates of the program are equipped for employment in industry. Graduates are prepared for graduate study in materials science and engineering and related fields.

Required Materials Science Courses
Students are required to take 13 Materials Science courses for a total of 37 points. The required courses are MSAE E3010, E3012, E3013, E3156, E3157, E4100, E4102, E4200, E4201, E4202, E4206, E4215, and E4250.

Technical Elective Requirements
Students are required to take nine technical electives (27 points) from the list given below, which offers significant flexibility in allowing students to tailor their degree program to their interests.

a. All 3000-level or higher courses in the Materials Science program of the Department of Applied Physics and Applied Mathematics, except those MSAE courses that are required.

b. All 3000-level or higher courses in Applied Physics or Applied Math Programs of the Department of Applied Physics and Applied Mathematics.

c. All 3000-level or higher courses in the Department of Biomedical Engineering, Civil Engineering and Engineering Mechanics program, Department of Chemical Engineering, Department of Computer Science, Department of Earth and Environmental Engineering, Department of Electrical Engineering, Department of Industrial Engineering and Operations Research, and Department of Mechanical Engineering, except for courses that require graduate standing.

d. ORCA E2500 Foundations of data science

e. Courses in the Department of Chemistry listed in the Focus Areas below.

Focus Areas for technical electives are listed below. Students may choose from any one area if they so choose. They are not required to do so.

NANOMATERIALS
APPH E3100y: Intro to quantum mechanics
CHEM GU4071x: Inorganic chemistry
MSAE E4090y: Nanotechnology
APPH E4100x: Quantum physics of matter
CHEM GU4168x: Materials chemistry, I
ELEN E4193x: Modern display technology
MECE E4212x or y: Microelectromechanical systems
# Materials Science Program: First and Second Years

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<tr>
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<th>Semester I</th>
<th>Semester II</th>
<th>Semester III</th>
<th>Semester IV</th>
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<tbody>
<tr>
<td><strong>Mathematics</strong></td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0) either semester</td>
<td>and APMA E2101 (3)</td>
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<tr>
<td><strong>Physics</strong> (three tracks, choose one)</td>
<td>UN1401 (3)</td>
<td>UN1601 (3.5)</td>
<td>UN1402 (3)</td>
<td>UN1403 (3)</td>
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<tr>
<td></td>
<td>UN2801 (4.5)</td>
<td>UN2802 (4.5)</td>
<td>UN1602 (3.5)</td>
<td>UN2601 (3.5)</td>
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<tr>
<td><strong>Chemistry</strong></td>
<td>UN1403 (4) or UN1404 (4) or UN2045 (4) or UN1604 (4)</td>
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<tr>
<td><strong>Required Lab</strong></td>
<td>PHYS UN1493 (3) or UN3081 (2) or CHEM UN1500 (3) or UN1507 (3) or UN3085 (4)</td>
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<tr>
<td><strong>University Writing</strong></td>
<td>CC1010 (3) either semester</td>
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<tr>
<td><strong>Non-Technical Requirements</strong></td>
<td>HUMA CC1001, COCI CC1101, or Global Core (3–4); HUMA UN1121 (3) or UN1123 (3); HUMA CC1002, COCI CC1102, or Global Core (3–4); ECON UN1105 (4) and UN1155 recitation (0)</td>
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<tr>
<td><strong>Physical Education</strong></td>
<td>UN1001 (f)</td>
<td>UN1002 (f)</td>
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<tr>
<td><strong>The Art of Engineering</strong></td>
<td>ENGI E1102 (4) either semester</td>
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<tr>
<td><strong>Computer Science</strong></td>
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<td></td>
<td>ENGI E1006 (3) any semester</td>
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<tr>
<td><strong>Technical Requirements</strong></td>
<td></td>
<td></td>
<td>MSAE E3010 (3) Foundations of materials science</td>
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1 Some of non-tech courses can be postponed to junior or senior year, so lab courses MSAE E3012 and MSAE E3013 can be taken along with MSAE E3010.
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<tr>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
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<tr>
<td><strong>REQUIRED COURSES</strong></td>
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</table>
| MSAE E3012 (3)  
Laboratory in mat. sci. I | MSAE E3013 (3)  
Laboratory in mat. sci. II | MSAE E3156 (2)  
Design project | MSAE E3157 (2)  
Design project |
| MSAE E4100 (3)  
Crystallography | MSAE E4201 (3)  
Materials thermodynamics and phase diagrams | MSAE E4200 (3)  
Theory of crystalline materials | MSAE E4202 (3)  
Kinetics of transformations in materials |
| MSAE E4102 (3)  
Synthesis and processing of materials | MSAE E4250 (3)  
Ceramics and composites | MSAE E4206 (3)  
Electronic and magnetic properties of solids | MSAE E4215 (3)  
Mechanical behavior of materials |
| **TECHNICAL ELECTIVES** | Students must complete 27 units of Technical Electives. | | |
| **NONTECHNICAL ELECTIVES** | Students must complete the 27-point requirement.² | | |

¹Motivated students are highly encouraged to take the materials science laboratory I and II courses in the sophomore year to obtain practical understanding of material covered in the junior and senior years.
²See page 9 or seas.columbia.edu for details (administered by the advising dean).

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<tr>
<td><strong>REQUIRED COURSES</strong></td>
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</tbody>
</table>
| MSAE E3010 (3)  
Foundations of materials science and engineering | MSAE E3013 (3)  
Laboratory in materials science, II | MSAE E3156 (2)  
Design project | MSAE E3157 (2)  
Design project |
| MSAE E3012 (3)  
Laboratory in materials science, I | MSAE E4201 (3)  
Materials thermodynamics and phase diagrams | MSAE E4200 (3)  
Theory of crystalline materials | MSAE E4202 (3)  
Kinetics of transformations in materials |
| MSAE E4102 (3)  
Synthesis and processing of materials | MSAE E4250 (3)  
Ceramics and composites | MSAE E4206 (3)  
Electronic and magnetic properties of solids | MSAE E4215 (3)  
Mechanical behavior of materials |
| **TECHNICAL ELECTIVES** | Students must complete 27 or 24 units of Technical Electives.¹ | | |
| **NONTECHNICAL ELECTIVES** | Students must complete the 27-point requirement.² | | |

¹Students transferring from another SEAS department into the Materials Science program in the junior year must complete the 27 units of technical elective requirement; Combined Plan 3/2 transfer students must complete 24 units of technical electives.
²Students transferring from another SEAS department into the Materials Science program in the junior year must complete the 27-point requirement; see page 9 or seas.columbia.edu for details (administered by the advising dean). Combined Plan 3/2 transfer students do not need nontechnical electives; see page 14 or seas.columbia.edu.
BMEN E4310x or y: Solid biomechanics
BMEN E4450y: Dental and craniofacial tissue engineering
BMEN E4501x: Tissue engineering, I: biomaterials and scaffold design
CHEE E4530y: Corrosion of metals
BMEN E4550x: Micro- and nanostructures in cellular engineering

* Note that BIOL UN2005x: Introductory biology, I and BIOL UN2006y: Introductory biology, II are prerequisites for a number of courses in this track.

MATERIALS CHEMISTRY/SOFT MATERIALS
CHEM UN2443x-UN2444y: Organic chemistry
CHEN E4201: Applications of electrochemistry
CHEE E4252: Intro surface & colloid chemistry
CHEN E4620: Intro polymers/soft materials
CHEN E4640: Polymer surfaces and interfaces

Nontechnical Elective Requirements
All materials science students are also expected to register for nontechnical electives, both those specifically required by the School of Engineering and Applied Science and those needed to meet the 27-point total of nontechnical electives required for graduation.

Transfer Students
Combined Plan 3-2/Transfer students and students transferring from another SEAS department into the Materials Science Program in the junior year (upon approval of the Materials Science Undergraduate Transfer Committee) will take the following courses to satisfy the degree requirements: The required courses are MSAE E3010, E3012, E3013, E3156, E3157, E4100, E4102, E4200, E4201, E4202, E4206, E4215, and E4250.

Combined Plan 3-2/Transfer Students will be guided by their academic advisers to avoid duplication of courses previously taken. The course tables describe the four-semester program schedule of courses leading to the bachelor’s degree in the Materials Science Program of the Department of Applied Physics and Applied Mathematics.

GRADUATE PROGRAMS IN MATERIALS SCIENCE AND ENGINEERING
M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

Master of Science Degree
Candidates for the Master of Science degree in Materials Science and Engineering will follow a program of study formulated in consultation with and approved by a faculty adviser. Thirty points of credit (typically ten three-point courses) are required for the degree. The requirements include:

- 18 points, MSAE 4000-, 6000-, 8000-level courses (max three points of research)
- Six (6) points, approved electives (see following list) or MSAE courses
- Six (6) points, general electives

Of the 30 points of credit required for the MS degree, 18 points of MSAE4000-, 6000-, or 8000-level courses must be included. Only three points of research (MSAE6273 or other research course) may be used to satisfy the MSAE point requirement. A minimum of six points of MSAE courses must be taken in the first semester. Furthermore, it is expected that 15 of the first 24 points taken will be in MSAE courses; any exceptions must be approved by a faculty adviser.

Six points of electives may be chosen either from MSAE courses, or from the following list of approved electives; a course not on the approved list can be counted only with prior, written approval.

Six points of electives may be chosen freely. These electives may include MSAE courses, approved electives, other electives, or an additional three points of research, with a maximum of six points of research counted toward the degree requirements. No undergraduate courses (3000-level or below) may be counted toward the degree.

Students interested in a specific focus in metallurgy or other areas in materials science and engineering should consult their faculty adviser for relevant course listings.

Electives:
MSAE E4000-, 6000- or 8000-level courses, except MSAE E6100
APCH E4080: Soft condensed matter
APMA E4101: Dynamical systems
APMA E4200: Partial differential equations
APMA E4204: Functions of a complex variable
APMA E4300: Computational mathematics: intro to numerical methods
APPH E4100: Quantum physics of matter
APPH E4110: Modern optics
APPH E4112: Laser physics
APPH E4200: Physics of fluids
APPH E4300: Applied electrodynamics
APPH E4990: Special topics in applied physics
APPH E6081: Solid state physics
BMEN E4300: Solid biomechanics
BMEN E4580: Foundations of nanobioscience and nanobiotechnology
CEEM E4113: Advanced mechanics of solids
CEEM E4114: Mechanics of fracture and fatigue
CIEN E4021: Elastic and plastic analysis of structures
CHEN E4201: Engineering applications of electrochemistry
CHEN E4630: Topics in soft materials
CHEN E4880: Atomic simulations for science and engineering
EEAE E4252: Introduction to surface and colloidal chemistry
ELEN E4193: Modern display science and technology
ELEN E4411: Fundamentals of photonics
ELEN E4944/6945: Principles of device microfabrication
ELEN E6412: Lightwave Devices
ELEN E6331/6333: Semiconductor device physics
IEOR E4150: Introduction to probability and statistics
MECE E4212: Microelectromechanical systems
MECE E4213: BioMEMS: design, fabrication, and analysis
MECE E4214: MEMS production and packaging
MECE E4610: Advanced manufacturing processes
MECE E6137: Nanoscale actuation and sensing
STAT GU4001: Introduction to probability and statistics

All degree requirements must be completed within five years. A candidate is required to maintain at least a 2.5 GPA. Applicants for admission are required to take the Graduate Record Examinations.

Professional Degree; Metallurgical Engineer
The program is designed for engineers who wish to do advanced work beyond the level of the M.S. degree but who do not desire to emphasize research. Admissions requirements include the undergraduate engineering degree, minimum 3.0 GPA, and GRE.

Candidates must complete at least 30
credits of graduate work beyond the M.S., or 60 points of graduate work beyond the B.S. No thesis is required. All degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

Coursework includes five core required courses and five elective courses from a pre-approved list of choices.

Core courses:

- EAAE E4001 Industrial ecology of earth resources
- EAAE E4009 Geographic information systems (GIS) for resource, environmental and infrastructure management
- EAAE E4160 Solid and hazardous waste materials
- EAAE E4900 Applied transport/chemical rate phenomena
- EAAE E6255-6 Methods and applications of analytical decision making in mineral industries

Elective courses must be five courses at the 4000 or higher level from within the Earth and Environmental Engineering Department, the Chemical Engineering Department, Materials Science Program, or others as approved by the adviser. These include but are not limited to: EAAE E4150, CHEE E4252, CIEE E4252, EAAE E4256, EAAE E4257, EAAE E6208. Although it is not required, interested students may choose to complete up to six credits in MSAE E9259-60.

**Doctoral Program**

At the end of the first year of graduate study in the doctoral program, candidates are required to take a comprehensive written qualifying examination, which is designed to test the ability of the candidate to apply coursework in problem solving and creative thinking. The standard is first-year graduate level. There are two four-hour examinations over a two-day period.

Candidates in the program must take the oral examination in the spring semester of their second year. Candidates must submit a written proposal and defend it orally before a Thesis Proposal Defense Committee consisting of three members of the faculty, including the adviser in the spring semester of their third year. Doctoral candidates must submit a thesis to be defended before a Dissertation Defense Committee consisting of five faculty members, including two professors from outside the doctoral program. Requirements for the Eng. Sc.D. (administered by the School of Engineering and Applied Science) and the Ph.D. (administered by the Graduate School of Arts and Sciences) are listed elsewhere in this bulletin.

**Areas of Research**

Materials science and engineering is concerned with synthesis, processing, structure, and properties of metals, ceramics, and other materials, with emphasis on understanding and exploiting relationships among structure, properties, and applications requirements. Our graduate research programs encompass research areas as diverse as polycrystalline silicon, electronic ceramics grain boundaries and interfaces, microstructure and stresses in microelectronics thin films, oxide thin films for novel sensors and fuel cells, optical diagnostics of thin-film processing, ceramic nanocomposites, electrodeposition and corrosion processes, structure, properties, and transmission electron microscopy and crystal orientation mapping, magnetic thin films for spintronic applications, chemical synthesis of nanoscale materials, nanocrystals, two-dimensional materials, nanostructure analysis using X-ray and neutron diffraction techniques, and electronic structure calculation of materials using density functional and dynamical mean-field theories. Application targets for polycrystalline silicon are thin film transistors for active matrix displays and silicon-on-insulator structures for ULSI devices. Novel applications are being developed for oxide thin films, including uncooled IR focal plane arrays and integrated fuel cells for portable equipment.

Thin film synthesis and processing in this program include evaporation, sputtering, electrodeposition, and plasma and laser processing. For analyzing materials structures and properties, faculty and students employ electron microscopy, scanning probe microscopy, photoluminescence, magnetotransport measurements, and X-ray diffraction techniques. Faculty members have research collaborations with IBM, and other New York area research and manufacturing centers, as well as major international research centers. Scientists and engineers from these institutions also serve as adjunct faculty members at Columbia. The National Synchrotron Light Source at Brookhaven National Laboratory is used for high-resolution X-ray diffraction and absorption measurements.

Entering students typically have undergraduate degrees in materials science, metallurgy, physics, chemistry, or other science and engineering disciplines. First-year graduate courses provide a common base of knowledge and technical skills for more advanced courses and for research. In addition to coursework, students usually begin an association with a research group, individual laboratory work, and participation in graduate seminars during their first year.

**GRADUATE SPECIALTY IN SOLID-STATE SCIENCE AND ENGINEERING**

Solid-state science and engineering is an interdepartmental graduate specialty that provides coverage of an important area of modern technology that no single department can provide. It encompasses the study of the full range of properties of solid materials, with special emphasis on electrical, magnetic, optical, and thermal properties. The science of solids is concerned with understanding these properties in terms of the atomic and electronic structure of the materials in question. Insulators (dielectrics), semiconductors, ceramics, and metallic materials are all studied from this viewpoint. Quantum and statistical mechanics are key background subjects. The engineering aspects deal with the design of materials to achieve desired properties and the assembling of materials into systems to produce devices of interest to modern technology, e.g., for computers and for energy production and utilization.

**Areas of Research**

The graduate specialty in solid-state science and engineering includes research programs in metamaterials and infrared optoelectronic devices.
Program of Study

The applicant for the graduate specialty must be admitted to one of the participating programs: applied physics and applied mathematics, or electrical engineering. A strong undergraduate background in physics or chemistry and in mathematics is important.

The doctoral student must meet the formal requirements for the Eng. Sc.D. or Ph.D. degree set by the department in which they are registered. However, the bulk of the program for the specialty will be arranged in consultation with a member of the interdepartmental Committee on Materials Science and Engineering/ Solid-State Science and Engineering. At the end of the first year of graduate study, doctoral candidates are required to take a comprehensive written examination concentrating on solid-state science and engineering.

The following are regarded as core courses of the specialty:

- APPH E4100: Quantum physics of matter
- APPH E4110: Modern optics
- APPH E4112: Laser physics
- APPH E6081: Solid-state physics
- CHEM GU4230: Statistical thermodynamics
- CHAP E4120: Statistical mechanics
- ELEN E4301: Intro to semiconductor devices
- ELEN E4944: Principles of device microfabrication

**ELEN E6331-E6332:** Principles of semiconductor physics

**ELEN E6403:** Classical electromagnetic theory

or

**PHYS GR6092:** Electromagnetic theory, I

**MSAE E4100:** Crystallography

**MSAE E4206:** Electronic and magnetic properties of solids

**PHYS GR6018:** Physics of the solid state

**PHYS GR6037:** Quantum mechanics

**COURSES IN MATERIALS SCIENCE AND ENGINEERING**

For related courses, see also Applied Physics and Applied Mathematics, Chemical Engineering, Earth and Environmental Engineering, Electrical Engineering, and Mechanical Engineering.

**MSAE E3010x Foundations of materials science**

3 pts. Lect: 3. Professor Noyan.
Pre/Prerequisite(s): CHEM UN1404 and PHYS UN1011. Introduction to quantum mechanics: atoms, electron shells, bands, bonding; introduction to group theory: crystal structures, symmetry, crystallography; introduction to materials classes: metals, ceramics, polymers, liquid crystals, nanomaterials; introduction to polycrystals and disordered materials; noncrystalline and amorphous structures; grain boundary structures, diffusion; phase transformations; phase diagrams, time-temperature-transformation diagrams; properties of single crystals: optical properties, electrical properties, magnetic properties, thermal properties, mechanical properties, and failure of polycrystalline and amorphous materials.

**MSAE E3012x Laboratory in materials science, I**

3 pts. Lect: 3. Professor Noyan.
Pre/Corequisite: MSAE E3010. Measurement of electrical, thermal, and magnetic properties of single crystals. Single crystal diffraction analysis, polarized light microscopy, and infrared microscopy in Si single crystals, written and oral reports. This is the second of a two-semester sequence materials laboratory course.

**MSAE E3013y Laboratory in materials science, II**

3 pts. Lect: 3. Professor Noyan.
Pre/Prerequisite(s): MSAE E3012. Metallurgical sample preparation, optical microscopy, quantitative metallography, hardness and tensile testing, plastic deformation, annealing, phase diagrams, brittle fracture of glass, temperature and strain-rate dependent deformation of polymers; written and oral reports. This is the second of a two-semester sequence materials laboratory course.

**MSAE E3111x Thermodynamics, kinetic theory and statistical mechanics**

3 pts. Lect: 3. Professor Bailey.
An introduction to the basic thermodynamics of systems, including concepts of equilibrium, entropy, thermodynamic functions, and phase changes. Basic kinetic theory and statistical mechanics, including diffusion processes, concept of phase space, classical and quantum statistics, and applications thereof.

**MSAE E3141y Processing of metals and semiconductors**

3 pts. Lect: 3. Not offered in 2022–2023. Prerequisite(s): MSAE E3011 or equivalent. Synthesis and production of metals and semiconductors with engineered microstructures for desired properties. Includes high-temperature, aqueous, and electrochemical processing; thermal and mechanical processing of metals and alloys; casting and solidification; diffusion, microstructural evolution, and phase transformations; modification and processing of surfaces and interfaces; deposition and removal of thin films. Processing of Si and other materials for elemental and compound semiconductor-based electronic, magnetic, and optical devices.

**MSAE E3142y Processing of ceramics and polymers**


**MSAE E3156x-E3157y Design project**

2 pts (each semester). Lect.: 3. Professor Yang.
Pre/Prerequisite(s): Senior standing. Written permission from instructor and approval from adviser. E3156: A design problem in materials science or metallurgical engineering selected jointly by the student and a professor in the department. The project requires research by the student, directed reading, and regular conferences with the professor in charge. E3157: Completion of the research, directed reading, and conferences, culminating in a written report and an oral presentation to the department.

**MSAE E3900x and y Undergraduate research in materials science**

0–4 pts. Members of the faculty.
Pre/Prerequisite(s): Written permission from instructor and approval from adviser. May be repeated for credit, but no more than 6 points may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in materials science or carry out a special project under the supervision of the staff. Credit is contingent upon the submission of an acceptable thesis or final report.
MSAE E4090y Nanotechnology
Prerequisite(s): APPH E3100 and MSAE E3010 or their equivalents with instructor’s permission. The science and engineering of creating materials, functional structures and devices on the nanometer scale. Carbon nanotubes, nanocrystals, quantum dots, size dependent properties, self-assembly, nanostructured materials. Devices and applications, nanofabrication. Molecular engineering, bionanotechnology. Imaging and manipulating at the atomic scale. Nanotechnology in society and industry. Offered in alternate years.

MSAE E4100x Crystallography
3 pts. Lect: 3. Professor Barmak.
Prerequisite(s): CHEM UN1403, PHYS UN1403, APMA E2101, or equivalent. A first course on crystallography. Crystal symmetry, Bravais lattices, point groups, space groups. Diffraction and diffracted intensities. Exposition of typical crystal structures in engineering materials, including metals, ceramics, and semiconductors. Crystalline anisotropy.

MSAE E4102x Synthesis and processing of materials
3 pts. Lect: 3. Professor Im.
Prerequisite(s): MSAE E3010 or equivalent or instructor’s permission. A course on synthesis and processing of engineering materials. Established and novel methods to produce all types of materials (including metals, semiconductors, ceramics, polymers, and composites). Fundamental and applied topics relevant to optimizing the microstructure of the materials with desired properties. Synthesis and processing of bulk, thin-film, and nano materials for various mechanical and electronic applications.

MSAE E4105x Ceramic nanomaterials
Prerequisite(s): CHEM UN1404 or equivalent undergraduate thermodynamics. Ceramic nanomaterials and nanostructures: synthesis, characterization, size-dependent properties, and applications; surface energy, surface tension and surface stress; effect of ligands, surfactants, adsorbents, isoelectric point, and surface charges; supersaturation and homogenous nucleation for monodispersity.

MSAE E4132y Fundamentals of polymers and ceramics
Prerequisite(s): MSAE E3010 or instructor's permission. The science and engineering of polymer, ceramic and composite inorganic materials. Fundamental aspects of structure, processing and properties. Polymers: classification, synthesis, elastomers, thermoplastics, thermosets; ceramics: Crystal structure, morphology, classification, oxides, nitrates, carbides, silicates. Electrical, mechanical, thermal and optical properties. Common and advanced technological applications, electrical/optical devices, catalytic and environmental applications.

MSAE E4200x Theory of crystalline materials: phonons
3 pts. Lect: 3. Professor Marianetti.
Pre/Corequisite: MSAE E4100 or instructor’s permission. Phenomenological theoretical understanding of vibrational behavior of crystalline materials; introducing all key concepts at classical level before quantizing the Hamiltonian. Basic notions of Group Theory introduced and exploited: irreducible representations, Great Orthogonality Theorem, character tables, degeneration, product groups, selection rules, etc. Both translational and point symmetry employed to block diagonalize the Hamiltonian and compute observables related to vibrations/phonons. Topics include band structures, density of states, band gap formation, nonlinear (anharmonic) phenomena, elasticity, thermal conductivity, heat capacity, optical properties, ferroelectricity. Illustrated using both minimal model Hamiltonians in addition to accurate Hamiltonians for real materials (e.g., Graphene).

MSAE E4202y Theory of crystalline materials: electrons
3 pts. Lect: 3. Professor Marianetti.
Pre/Corequisite: MSAE E4200 or instructor’s permission. Phenomenological theoretical understanding of electrons in crystalline materials. Both translational and point symmetry employed to block diagonalize the Schrödinger equation and compute observables related to electrons. Topics include nearly free electrons, tight-binding, electron-electron interactions, transport, magnetism, optical properties, topological insulators, spin-orbit coupling, and superconductivity. Illustrated using both minimal model Hamiltonians in addition to accurate Hamiltonians for real materials.

MSAE E4206x Electronic and magnetic properties of solids
3 pts. Lect: 3. Professor Bailey.
Prerequisite(s): PHYS UN1401-3 or equivalent. A survey course on the electronic and magnetic properties of materials, oriented toward materials for solid-state devices. Dielectric and magnetic properties, ferroelectrics and ferromagnets. Conductivity and superconductivity. Electronic band theory of solids: classification of metals, insulators, and semiconductors. Materials in devices: examples from semiconductor lasers, cellular telephones, integrated circuits, and magnetic storage devices. Topics from physics are introduced as necessary.

MSAE E4215y Mechanical behavior of structural materials
3 pts. Lect: 3. Professor Bailey.
Prerequisite(s): MSAE E3010. Recommended preparation: A course in mechanics of materials. Review of states of stress and strain and their relations in elastic, plastic, and viscous materials. Dislocation and elastic-plastic concepts introduced to explain work hardening, various materials-strengthening mechanisms, ductility, materials devices, material reliability and fracture, and toughness. Macroscopic and microstructural aspects of brittle and ductile fracture mechanics, creep and fatigue phenomena. Case studies used throughout, including flow and fracture of structural alloys, polymers, hybrid materials, composite materials, ceramics, and electronic prevention emphasized.

MSAE E4250x Ceramics and composites
3 pts. Lect: 3 Professor Chan.
Pre/Corequisites: MSAE E3010 and E3013, or instructor’s permission. Will cover some of the fundamental processes of atomic diffusion, sintering and microstructural evolution, defect chemistry, ionic transport, and electrical properties of ceramic materials. Following this, we will examine applications of ceramic materials, specifically, ceramic thick and thin film materials in the areas of sensors and energy conversion/storage devices such as fuel cells, and batteries. The coursework level assumes that the student has already taken basic courses in the thermodynamics of materials, diffusion in materials, and crystal structures of materials.

MSAE E4260y Electrochemical materials and devices: from structure to performance
Prerequisite(s): CHEM UN1403, MSAE E3010, equivalents, or instructor's permission. Overview of electrochemical processes and applications from perspectives of materials and devices. Thermodynamics and principles of electrochemistry, methods to characterize electrochemical processes, application of electrochemical materials and devices, including batteries, supercapacitors, fuel cells, electrochemical sensor, focus on link between material structure, composition, and properties with electrochemical performance.

MSAE E4301x Materials science laboratory
Prerequisite(s): Introductory materials course or equivalent and instructor’s permission. General experimental techniques in materials science, including X-ray diffraction, scanning electron microscopes, atomic force microscopy, materials synthesis and thermodynamics, characterization of material properties (mechanical, electrochemi-
MSAE E4990x and y Special topics in materials science and engineering
1–3 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. May be repeated for credit. Topics and instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

MSAE E4999x or y–S4999 Supervised internship
1–3 pts. Members of the faculty.
Prerequisite(s): Internship and approval from adviser must be obtained in advance. Only for master’s students in the Department of Applied Physics and Applied Mathematics who may need relevant work experience as part of their program of study. Final report required. May not be taken for pass/fail or audited.

MSAE E6085y Computing the electronic structure of complex materials
3 pts. Lect: 3. Professor Wentzcovitch.
Prerequisite(s): APPH E3100 or equivalent. Basics of density functional theory (DFT) and its application to complex materials. Computation of electronics and mechanical properties of materials. Group theory, numerical methods, basis sets, computing, and running open source DFT codes. Problem sets and a small project.

MSAE E6091y Magnetism and magnetic materials

MSAE E6100y Transmission electron microscopy
3 pts. Lect: 3. Not offered in 2022–2023. Theory and practice of transmission electron microscopy (TEM): principles of electron scattering, diffraction, and microscopy; analytical techniques used to determine local chemistry; introduction to sample preparation; laboratory and in-class remote access demonstrations, several hours of hands-on laboratory operation of the microscope; the use of simulation and analysis software; guest lectures on cryomicroscopy for life sciences and high resolution transmission electron microscopy for physical sciences; and, time permitting, a visit to the electron microscopy facility in the Center for Functional Nanomaterials (CFN) at the Brookhaven National Laboratory (BNL).

MSAE E6229y Energy and particle beam processing of materials

MSAE E6230y Kinetics of phase transformations

MSAE E6251y Thin films and layers
3 pts. Lect: 3. Professor Chan. Vacuum basics, deposition methods, nucleation and growth, epitaxy, critical thickness, defects properties, effect of deposition procedure, mechanical properties, adhesion, interconnects, and electromigration.

MSAE E6273x and y–S6273 Materials science reports
0 to 6 pts. Members of the faculty.
Prerequisite(s): Written permission from instructor and approval from adviser. Formal written reports and conferences with the appropriate member of the faculty on a subject of special interest to the student but not covered in the other course offerings.

MSAE E8235x and y Selected topics in materials science
3 pts. Lect: 3. Not offered in 2022–2023. May be repeated for credit. Selected topics in materials science. Topics and instructors change from year to year. For students in engineering, physical sciences, biological sciences, and related fields.

MSAE E9000x and y Materials science and engineering colloquium
0 pt. Professor Yang. Speakers from universities, national laboratories, and industry are invited to speak on the recent impact of materials science and engineering innovations.

MSAE E9259x–E9260y Research topics in materials science and metallurgical engineering
1 pt. Lect: 1. Members of the faculty. Discussion of a group of technical papers related to a topic of current research interest.

MSAE E9301x–S9301 Doctoral research instruction
0–15 pts. Members of the faculty. Prerequisite(s): Qualifying examination for doctorate. Required of doctoral candidates.

MSAE E9309x and y–S9309 Proposal of research for the doctorate
0–3 pts. Members of the faculty. A written report prepared by the prospective doctoral candidate defining the proposed research for the dissertation, and oral defense of the proposal.

MSAE E9800x and y–S9800 Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty. A candidate for the Eng.Sc.D. degree must register for 12 points of doctoral research instruction. Registration in MSAE E9800 may not be used to satisfy the minimum residence requirement for the degree.

MSAE E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty. A candidate for the doctorate may be required to register for this course every term after the coursework has been completed and until the dissertation has been accepted.
Machinery engineering is a diverse subject that derives its breadth from the need to design and manufacture everything from small individual parts/devices (e.g., microscale sensors, inkjet printer nozzles) to large systems (e.g., spacecraft and machine tools). The role of a mechanical engineer is to take a product from an idea to the marketplace. In order to accomplish this, a broad range of skills are needed. The particular skills in which the mechanical engineer acquires deeper knowledge are the ability to understand the forces and the thermal environment that a product, its parts, or its subsystems will encounter; design them and ensure they will operate without failure. Perhaps the one skill that allows them to design an exciting product or system, the ability to design, market, and produce a system. These skills also prove to be valuable in other endeavors and can launch a career in medicine, law, consulting, management, banking, finance, and so on.

For those interested in applied scientific and mathematical aspects of the discipline, graduate study in mechanical engineering can lead to a career of research and teaching.

**Current Research Activities**

Current research activities in the Department of Mechanical Engineering are in the areas of controls and robotics, energy and micropower generation, fluid mechanics, heat/mass transfer, mechanics of materials, manufacturing, material processing, MEMS, nanotechnology, and biomechanics and biofluids.

**Biomechanics, Biofluids, and Mechanics of Materials.** Some of the current research in biomechanics
is concerned with the application of continuum theories of mixtures to problems of electromechanical behavior of soft biological tissues, contact mechanics, lubrication of diarthroial joints, and cartilage tissue engineering. (Ateshian)

The Kysar group studies the mechanics and mechanical properties of small-scale structures and materials. Examples of material systems include two-dimensional materials such as graphene, nanoporous metal thin films, metallic and polymeric composites containing nanoscale strengthening agents, single crystal metals, and the ear’s round Window Membrane, among several others. The work is experimental, theoretical, and computational in nature. The ultimate goal is to understand and predict the mechanical behavior based on fundamental physics and chemistry through the development of multiple length scale models.

At the Kasza Living Materials Lab we are interested in how cells self-organize to build tissues and organs with mechanical properties that are required for proper function. A major focus is to uncover fundamental mechanical and biological mechanisms that coordinate the behaviors of cells in developing tissues. To do this, we study morphogenesis in developing embryos of model organisms and combine approaches such as in vivo imaging, optogenetics, and biomechanical measurements. We are leveraging this knowledge to design and build novel cell-based tissue structures and systems. Our goals are to shed light on human health and disease and learn how to better build functional tissues in the lab.

Other areas of biomechanics include characterizing the structure-function behavior of the cervix during the remodeling events of pregnancy and characterizing the mechanical properties of the eye-wall in relation to glaucoma. Research in our lab includes the mechanical testing of biological soft tissues, the biochemical analysis of tissue microstructure, and material modeling based on structure-mechanical property relationships. In collaboration with clinicians, our goal is to understand the etologies of tissue pathology and disease. (Myers)

A surgically implantable pediatric valve device that can ‘grow with the child’ would revolutionize current treatment for neonates born with valve disease. In close collaboration with Dr. David Kalfa, who is a pediatric heart surgeon at Columbia University Medical Center, and Dr. Haim Waisman from the Civil Engineering department, the Kysar and Vedula groups are involved in a multidisciplinary NIH-funded project to develop an expendable biostable polymericvalved conduit. The device would be implanted surgically to reconstruct the right ventricular outflow tract in neonates and then expanded by successive transcatheter procedures to reach the adult size. This project involves material design and characterization of the growth potential of a viscoelastic polymer, numerically model the fluid-structure interaction of the valved conduit, optimization for valve competence at every stage of expansion, and assess the biocompatibility and durability in animal models. (Kysar, Vedula)

Control, Robotics, Design, and Manufacturing. Control research emphasizes iterative learning control (ILC) and repetitive control (RC). ILC creates controllers that learn from previous experience performing a specific command, such as robots on an assembly line, aiming for high-precision mechanical motions. RC learns to cancel repetitive disturbances, such as precision motion through gearing, machining, satellite precision pointing, particle accelerators, etc. Time optimal control of robots is being studied for increased productivity on assembly lines through dynamic motion planning. Research is also being conducted on improved system identification, making mathematical models from input-output data. The results can be the starting point for designing controllers, but they are also studied as a means of assessing damage in civil engineering structures from earthquake data. (Longman)

Robotics research focuses on design of novel rehabilitation machines and training algorithms for functional rehabilitation of neural impaired adults and children. The research also aims to design intelligent machines using nonlinear system theoretic principles, computational algorithms for planning, and optimization.

Robotic Systems Engineering (ROSE) Lab develops technology capable of solving difficult design problems, such as cable-actuated systems, under-actuated systems, and others. Robotics and Rehabilitation (ROAR) Lab focuses on developing new and innovative technologies to improve the quality of care and patient outcomes. The lab designs novel exoskeletons for upper and lower limbs training of stroke patients, and mobile platforms to improve socialization in physically impaired infants (Agrawal).

The Robotic Manipulation and Mobility (ROAM) Lab focuses on versatile manipulation and mobility in robotics, aiming for robotic applications pervasive in everyday life. Research areas include manipulation and grasping, interactive or Human-in-the-Loop robotics, dynamic simulators and virtual environments, machine perception and modeling, and many more. We are interested in application domains such as versatile automation in manufacturing and logistics, assistive and rehabilitation robotics in healthcare, space robotics, and mobile manipulation in unstructured environments. (Ciocarlie)

At the Creative Machines Lab (CreativeMachines.org) we are interested in robots that create and robots that are themselves creative. We develop novel autonomous systems that can design and make other machines—automatically. We are working on a self-replicating robots, self-aware robots, robots that improve themselves over time, and robots that compete and cooperate with other robots. We build robots that paint art, cook food, build bridges and fabricate other robots. Our work is inspired from biology, as we seek new biological concepts for engineering and new engineering insights into biology. (Lipson)

In the area of advanced manufacturing processes and systems, current research concentrates on laser materials processing. Investigations are being carried out in laser micromachining; laser forming of sheet metal; microscale laser shock-peening, material processing using improved laser-beam quality. Both numerical and experimental work is conducted using state-of-the-art equipment, instruments,
and computing facilities. Close ties with industry have been established for collaborative efforts. (Yao)

**Energy, Fluid Mechanics, and Heat/Mass Transfer.** In the area of energy, one effort is in energy systems with an eye toward cost-effective decarbonization using technologies that are at hand or near-ready. The interaction of the electric grid, with buildings, transportation, gas networks, storage and electrofuels is being studied. Another effort addresses the integration of thermal storage into HVAC systems for efficient use of variable renewable energy. The development of measurement, monitoring and control systems using IoT devices for use in micrositing and operation of microgrids and enabling flexibility or demand response of load. (Modi)

In the area of energy, demand estimation and prediction of interest using utility data, satellite imagery and lean, robust field data capture. (Modi)

In the area of nanoscale thermal transport, our research efforts center on the enhancement of thermal radiation transport across interfaces separated by a nanoscale gap. The scaling behavior of nanoscale radiation transport is measured using a novel heat transfer measurement technique based on the deflection of a bimaterial atomic force microscope cantilever. Numerical simulations are also performed to confirm these measurements. The measurements are also used to infer extremely small variations of van der Waals forces with temperature. This enhancement of radiative transfer will ultimately be used to improve the power density of thermophotovoltaic energy conversion devices. (Narayanaswamy)

Also in the area of energy, research is being performed to improve the thermochemical models used in accelerating development of cleaner, more fuel-efficient engines through computational design. In particular, data-driven approaches to creating high-accuracy, uncertainty-quantified thermochemicals models are being developed that utilize both theoretical and experimental data. Special emphasis is placed on the generation and analysis of data across the full range of relevant scales—from the small-scale electronic behavior that governs molecular reactivity to the large-scale turbulent, reactive phenomena that govern engine performance. (Burke)

The Vedula group aims to advance clinical management of cardiovascular disease using computational modeling. We are developing novel computational techniques for performing patient-specific modeling of the cardiovascular system aimed at understanding the role of biomechanical factors in disease and development, device design, and ‘virtual’ surgery planning. Computational modeling combined with machine learning and data-mining strategies provides unprecedented opportunities to not only examine acute response to treatment, but also predict and risk stratify patients susceptible to long-term remodeling and dysfunction. (Vedula)

The Vedula group is involved in developing multiscale-multiphysics models of the heart coupling cardiac electrophysiology, tissue mechanics, blood flow and valvular interactions, thereby creating an integrated heart model, that could be used to study a variety of cardiac and valvular pediatric and adult cardiovascular disease. A few applications that we are particularly interested in include cardiomyopathies, valvular calcifications and device design, remodeling and dysfunction in congenital heart disease. (Vedula)

In the area of energy, the Building Physics and Energy Systems Laboratory aims to develop new modeling techniques to understand the dynamics of energy demand necessary to facilitate decarbonization in buildings. Research focuses on developing new modeling and simulation methods to provide more accurate estimates of time-vary demand, model-based control system to enable demand flexibility, and hybrid physics and statistical modeling approaches to provide accurate estimates of the timing of demand at the urban scale. (Howard)

**MEMS and Nanotechnology.** In these areas, research activities focus on power generation systems, nanostructures for photonics, fuel cells and photovoltaics, and microfabricated adaptive cooling skin and sensors for flow, shear, and wind speed. Basic research in fluid dynamics and heat/mass transfer phenomena at small scales also support these activities.

(Hone, Kysar, Lin, Modi, Narayanaswamy)

We study the dynamics of microcantilevers and atomic force microscope cantilevers to use them as microscale thermal sensors based on the resonance frequency shifts of vibration modes of the cantilever. Bimaterial microcantilever-based sensors are used to determine the thermophysical properties of thin films. (Narayanaswamy)

Research in the area of nanotechnology focuses on nanomaterials such as nanotubes and nanowires and their applications, especially in nanoelectromechanical systems (NEMS). A laboratory is available for the synthesis of graphene and other two-dimensional materials using chemical vapor deposition (CVD) techniques and to build devices using electron-beam lithography and various etching techniques. This effort will seek to optimize the fabrication, readout, and sensitivity of these devices for numerous applications, such as sensitive detection of mass, charge, and magnetic resonance. (Hone, Kysar, Modi)

Research in BioMEMS aims to design and create MEMS and micro/nanofluidic systems to control the motion and measure the dynamic behavior of biomolecules in solution. Current efforts involve modeling and understanding the physics of micro/ nanofluidic devices and systems, exploiting polymer structures to enable micro/nanofluidic manipulation, and integrating MEMS sensors with microfluidics for measuring physical properties of biomolecules. (Lin)

The Schuck group aims to characterize, understand, and control nanoscale light-matter interactions, with a primary focus on sensing, engineering, and exploiting novel optoelectronic phenomena emerging from nanostructures and interfaces. This offers unprecedented opportunities for developing innovative devices that rely on the dynamic manipulation of single photons and charge carriers. We are continuously developing new multimodal and multidimensional spectroscopic methods that provide unique access to optical, electrical, and structural properties at relevant length scales in real environments encountered in energy and biological applications. (Schuck)
Biotechnology. Active areas of research in the musculoskeletal biomechanics laboratory include theoretical and experimental analysis of articular cartilage mechanics; theoretical and experimental analysis of cartilage lubrication, cartilage tissue engineering, and bioreactor design; growth and remodeling of biological tissues; cell mechanics; and mixture theory for biological tissues with experiments and computational analysis (Ateshian).

The Hone laboratory studies two-dimensional (2D) materials such as graphene, with efforts spanning synthesis of single crystals and thin films; device fabrication; and testing of electronic, optical, mechanical, and other properties. The group develops methods to combine 2D materials into layered heterostructures, which are used to explore fundamental properties, achieve new functionality, and enable applications in electronics, photonics, sensing, and other areas. (Hone)

The Hone group uses nanofabrication and thin film techniques to create tools for studying the role of mechanical forces and geometry in cellular biology. These investigations seek to understand how cells sense the mechanical properties or physical shape of their surroundings, a process that plays a major role in maintaining healthy cellular and tissue function. (Hone)

Microelectromechanical systems (MEMS) are being exploited to enable and facilitate the characterization and manipulation of biomolecules. MEMS technology allows biomolecules to be studied in well-controlled micro/nanoenvironments of miniaturized, integrated devices, and may enable novel biomedical investigations not attainable by conventional techniques. The research interests center on the development of MEMS devices and systems for label-free manipulation and interrogation of biomolecules. Current research efforts primarily involve microfluidic devices that exploit specific and reversible, stimulus-dependent binding between biomolecules and receptor molecules to enable selective purification, concentration, and label-free detection of nucleic acid, protein, and small molecule analytes; miniaturized instruments for label-free characterization of thermodynamic and other physical properties of biomolecules; and subcutaneously implantable MEMS affinity biosensors for continuous monitoring of glucose and other metabolites. (Kysar, Lin)

The Kysar group has a project to design and develop a method to deliver therapeutics into the inner ear through the Round Window Membrane (RWM) that serves as a portal for acoustic energy between the middle ear and inner ear. This involves the design and fabrication of arrays of microneedles, the measurements of diffusive flux of chemical species across a perforated RWM, and the design, delivery, and testing of surgical tools, all in close collaboration with Anil K. Laiwani, M.D., at Columbia University Medical Center. (Kysar)

The Schuck group is involved in engineering novel near-infrared (NIR) upconverting nanoparticles (UCNPs) and UCNP-based microdevices for large-scale sensing applications, including deployment in projects aimed at deep-tissue imaging and the control of neural function deep within brain tissue. UCNPs have the potential to overcome nearly all limitations of current optical probes and sensors, which have run into fundamental chemical and photophysical incompatibilities with living systems. (Schuck)

Mass radiological triage is critical after a large-scale radiological event because of the need to identify those individuals who will benefit from medical intervention as soon as possible. The goal of the ongoing NIH-funded research project is to design a prototype of a fully automated, ultra high throughput biosimetry. This prototype is supposed to accommodate multiple assay preparation protocols that allow the determination of the levels of radiation exposure that a patient received. The input to this fully autonomous system is a large number of capillaries filled with blood of patients collected using finger sticks. These capillaries are processed by the system to distill the micronucleus assay in lymphocytes, with all the assays being carried out in situ in multiwell plates. The research effort on this project involves the automation system design and integration including hierarchical control algorithms, design and control of custom built robotic devices, and automated image acquisition and processing for sample preparation and analysis. (Yao)

A technology that couples the power of multidimensional microscopy (three spatial dimensions, time, and multiple wavelengths) with that of DNA array technology is investigated in an NIH-funded project. Specifically, a system is developed in which individual cells selected on the basis of optically detectable multiple features at critical time points in dynamic processes can be rapidly and robotically micromanipulated into reaction chambers to permit amplified DNA synthesis and subsequent array analysis. Customized image processing and pattern recognition techniques are developed, including Fisher’s linear discriminant preprocessing with neural net, a support vector machine with improved training, multiclass cell detection with error correcting output coding, and kernel principal component analysis. (Yao)

Facilities for Teaching and Research

The undergraduate laboratories, occupying an area of approximately 6,000 square feet of floor space, are the site of experiments ranging in complexity from basic instrumentation and fundamental exercises to advanced experiments in such diverse areas as automatic controls, heat transfer, fluid mechanics, stress analysis, vibrations, microcomputer-based data acquisition, and control of mechanical systems.

Equipment includes microcomputers and microprocessors, analog-to-digital and digital-to-analog converters, lasers and optics for holography and interferometry, a laser-Doppler velocimetry system, a particle image velocimetry system (PIV), a Schlieren system, dynamic strain indicators, a servoelectric material testing machine, photoelasticity, Digital Image Correlation (DIC) capabilities, a dynamometer, supersonic de Laval nozzle and subsonic wind tunnel, a cryogenic apparatus, a coordinate measurement machine (CMM), and three-dimensional printers as well as laser cutters. A CNC wire electrical discharge machine (EDM) is also available for the use of
specialized projects for students with prior arrangement. The undergraduate laboratory also houses experimental setups for the understanding and performance evaluation of a complete small steam power generation system, a heat exchanger, a solar cell system, a fuel cell system, a compressor, and a torsional control system. Part of the undergraduate laboratory is a staffed machine shop with machining tools such as CNC vertical milling machines, a CNC lathe, standard vertical milling machines, engine and bench lathes, surface grinder, band saw, drill press, tool grinders, a horizontal bandsaw, several Othermills used for light machining and circuit board fabrication.

The Mech Tech laboratory affords the opportunity for hands-on experience with microcomputer-embedded control of electromechanical systems. Facilities for the construction and testing of analog and digital electronic circuits aid the students in learning the basic components of the microcomputer architecture. The laboratory is divided into work centers for two-person student laboratory teams. Each work center is equipped with a mixed signal oscilloscope, several power supplies (for low-power electronics and higher power control), a function generator, a multimeter, a protoboard for building circuits, a microcomputer circuit board (which includes the microcomputer and

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<th>MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS</th>
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<tr>
<td>MATHS</td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0) and ORCA E2500 (3)(^6) either semester</td>
<td>APMA E2101 (3)(^1) or Linear Algebra (3)(^2) and ODE (3)(^3)</td>
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<tr>
<td>PHYSICS</td>
<td>UN1401 (3) UN1601 (3.5) UN2801 (4.5)</td>
<td>UN1402 (3) UN1602 (3.5) UN2802 (4.5)</td>
<td>UN1403 (3)(^4) UN2601 (3.5)(^4)</td>
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</tr>
<tr>
<td>CHEMISTRY</td>
<td>one semester lecture (3–4) UN1403 or UN1404 or UN2045 or UN1604</td>
<td>Lab UN1500 (3)(^5)</td>
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<tr>
<td>UNIVERSITY WRITING</td>
<td>CC1010 (3) either semester</td>
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<tr>
<td>REQUIRED NONTECHNICAL COURSES</td>
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<tr>
<td>REQUIRED TECHNICAL COURSES</td>
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<tr>
<td>COMPUTER SCIENCE</td>
<td>Computer language: COMS W1004 or COMS W1005 (3) or ENGI E1006 (3) (in semester I or III)</td>
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<tr>
<td>PHYSICAL EDUCATION</td>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
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<tr>
<td>THE ART OF ENGINEERING</td>
<td>ENGI E1102 (4) either semester</td>
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</table>

\(^1\) Students who take APMA E2101 must complete an additional 3 point course in math or basic science with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, or EEEB. One technical elective 3000-level or higher), with the approval of your ME faculty adviser, may be substituted for this purpose.

\(^2\) Linear algebra may be fulfilled by either APMA E3101 or MATH UN2010.

\(^3\) Ordinary differential equations may be fulfilled by either MATH UN2030 or MATH UN3027.

\(^4\) May substitute EEEB UN2001, BIOL UN2005, or higher.

\(^5\) May substitute Physics Lab UN1494 (3) or UN3081 (2).

\(^6\) Offered in spring semester.
peripheral components), a microcomputer programmer, and a personal computer that contains a data acquisition board. The data acquisition system serves as an oscilloscope, additional function generator, and spectrum analyzer for the student team. The computer also contains a complete microcomputer software development system, including editor, assembler, simulator, debugger, and C compiler. The laboratory is also equipped with a portable oscilloscope, an EPROM eraser (to erase microcomputer programs from the erasable chips), a logic probe, and an analog filter bank that the student teams share, as well as a stock of analog and digital electronic components.

The department maintains a modern computer-aided design laboratory equipped with thirty computer workstations with state-of-the-art design software. The research facilities are located within individual or group research laboratories in the department, and these facilities are being continually upgraded. To view the current research capabilities please visit the various laboratories within the research section of the department website. The students and staff of the department can, by prior arrangement, use much of the equipment in these research facilities. Through their participation in the NSF-MRSEC center, the faculty also have access to shared instrumentation and the clean room located in the Schapiro Center for Engineering and Physical Science Research. Columbia University’s extensive library system has superb scientific and technical collections.

Email and computing services are maintained by Columbia University Information Technology (CUIT) (columbia.edu/cuit).

UNDERGRADUATE PROGRAM
The Mechanical Engineering Undergraduate Program at Columbia University has the following Program Educational Objectives (PEOs) for its graduates:

1. Practice mechanical engineering in a broad range of industries.
2. Pursue advanced education, research and development, and other creative and innovative efforts in science, engineering, and technology, as well as other professional careers.
3. Conduct themselves in a responsible, professional, and ethical manner.
4. Participate in activities that support
humanity and economic development nationally and globally, developing as leaders in their fields of expertise.

As stated on the Mechanical Engineering department website, graduates of the Mechanical Engineering program at Columbia University will attain:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on teams whose members together provide leadership, create a

<table>
<thead>
<tr>
<th>MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS</th>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATHEMATICS</td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and E2001 (0) and ORCA E2500 (3)(^6) either semester</td>
<td>APMA E2101 (3)(^1) or Linear Algebra (3)(^2) and ODE (3)(^3)</td>
</tr>
<tr>
<td>PHYSICS (three tracks, choose one)</td>
<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>UN1403 (3)(^4)</td>
<td>UN2601 (3.5)(^4)</td>
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<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td>UN2602 (4.5)</td>
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<tr>
<td>CHEMISTRY</td>
<td>one semester lecture (3–4)</td>
<td>Lab UN1500 (3)(^5)</td>
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<td>REQUIRED NONTECHNICAL COURSES</td>
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<tr>
<td>REQUIRED TECHNICAL COURSES</td>
<td>ENME E3105 (4)</td>
<td>MECE E3414 (3)(^1)</td>
<td>ELEN E1201 (3.5) Intro. to elec. eng.</td>
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<tr>
<td></td>
<td>Mechanics</td>
<td>Mechanics of solids for mechanical engineers</td>
<td>MECE E3408 (3) Graphics and design</td>
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</tr>
<tr>
<td>COMPUTER SCIENCE</td>
<td>Computer language: COMS W1004 or COMS W1005 (3) or ENGI E1006 (3) (in semester I and III)</td>
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<td>ENGI E1102 (4) either semester</td>
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</table>

1 Students who take APMA E2101 must complete an additional 3 point course in math or basic science with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, or EEEB. One technical elective (3000-level or higher), with the approval of your ME faculty adviser, may be substituted for this purpose.
2 Linear algebra may be fulfilled by either APMA E3101 or MATH UN2010.
3 Ordinary differential equations may be fulfilled by either MATH UN2030 or MATH UN3027.
4 May substitute EEEB UN2001, BIOL UN2005, or higher.
5 May substitute Physics Lab UN1494 (3) or UN3081 (2).
6 Offered in spring semester.
7 Required for class of 2025 and beyond.
collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Highly qualified students are permitted to pursue an honors course consisting of independent study under the guidance of a member of the faculty.

Upon graduation the student may wish to enter employment in industry or government, or continue with graduate study. Alternatively, training in mechanical engineering may be viewed as a basis for a career in business, patent law, medicine, or management. Thus, the department’s undergraduate program provides a sound foundation for a variety of professional endeavors.

The program in mechanical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET, http://www.abet.org.

Undergraduates who wish to declare mechanical engineering as their major should do so prior to the start of their junior year. Students who declare in their first year should follow the Early Decision Track. Students who declare in their second year should follow the Standard Track. Students who wish to declare during or after the fall semester of their junior year must first obtain approval from the Mechanical Engineering Department.

Of the 18 points of elective content in the third and fourth years, at least 9 points of technical elective courses, including at least 6 points from the Department of Mechanical Engineering, must be taken. A technical elective can be any engineering course offered in the SEAS bulletin that is 3000 level or above. Those prior remaining points of electives are intended primarily as an opportunity to complete the four-year, 27-point nontechnical requirement. Consistent with professional accreditation standards, courses in engineering science and courses in design must have a combined credit of 48 points. Students should see their advisers for details.

Undergraduate students who intend to pursue graduate studies in engineering are strongly encouraged to take the combination of a stand-alone course in linear algebra (either APMA E3101 or MATH UN2010) and a stand-alone course in ordinary differential equations (either MATH UN2030 or UN3027), instead of the combined course.

### MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS

#### EARLY DECISION TRACK

<table>
<thead>
<tr>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
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</thead>
<tbody>
<tr>
<td><strong>REQUIRED COURSES</strong></td>
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</tr>
<tr>
<td>MECE E3018 (3) Lab I</td>
<td>MECE E3028 (3) Lab II</td>
<td>MECE E3409 (3) Machine design</td>
<td>MECE E3430 (3) Engineering design: creation</td>
</tr>
<tr>
<td>MECE E3100 (3) Fluids I</td>
<td>ENME E3106 (3) Dynamics and vibrations</td>
<td>MECE E3420 (3) Engineering design: concept</td>
<td></td>
</tr>
<tr>
<td>MECE E3301 (3) Thermodynamics</td>
<td>MECE E3311 (3) Heat transfer</td>
<td>EME E3601 (3) Classical control systems</td>
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<tr>
<td>MECE E1008 (1) Intro to machining (either semester)</td>
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<tr>
<td><strong>REQUIRED NONTECHNICAL COURSES</strong></td>
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<tr>
<td>HUMA UN1121 or UN1123 (3)</td>
<td>ECON UN1105 (4) and UN1155 recitation (0)</td>
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<tr>
<td><strong>TECHNICAL ELECTIVES¹</strong></td>
<td></td>
<td>9 points ³</td>
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<tr>
<td><strong>NONTECH ELECTIVES</strong></td>
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<tr>
<td>Students must complete the 27-point requirement.⁴</td>
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<tr>
<td><strong>TOTAL ESTIMATED POINTS²</strong></td>
<td>12</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

¹ If APMA E2101 is taken instead of Linear Algebra and ODE, students must complete an additional 3-point course in math or basic science with the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, or EEEB. One technical elective (3000-level or higher), with the approval of your ME faculty adviser, may be substituted for this purpose.
² Students must complete a minimum of 128 points to graduate.
³ 9 points required, 6 must be MECE courses.
⁴ See page 9, not required for Combined Plan students.
topics course APMA E2101. In addition, such students are encouraged to take a course in partial differential equations (APMA E3102 or E4200) as well as a course in numerical methods (APAM E3105 or APMA E4300) as technical electives. Ideally, planning for these courses should start at the beginning of the sophomore year.

Fundamentals of Engineering (FE) Exam
The FE exam is a state licensing exam and the first step toward becoming a Professional Engineer (P.E.). P.E. licensure is important for engineers to obtain—it shows a demonstrated commitment to professionalism and an established record of abilities that will help a job candidate stand out in the field. Ideally, the FE exam should be taken in the senior year while the technical material learned while pursuing the undergraduate degree is still fresh in the student’s mind. In addition to the FE exam, achieving P.E. licensure requires some years of experience and a second examination, which tests knowledge gained in engineering practice. For more information, please see http://ncees.org/exams/fe-exam/.

The Mechanical Engineering Department strongly encourages all seniors to take this exam and offers a review course covering material relevant to the exam, including a practice exam to simulate the testing experience. The FE exam is given in the fall and spring of each year. The review course is offered in the spring semester, concluding before the spring exam.

Integrated B.S./M.S. Program
The Integrated B.S./M.S. degree program is open to a qualified group of Columbia juniors and makes possible the earning of both the B.S. and M.S. degree in an integrated fashion. Benefits of this program include optimal matching of graduate courses with corresponding undergraduate prerequisites, greater ability to plan ahead for most advantageous course planning, opportunities to do research for credit during the summer after senior year, and up to 6 points of 4000-level technical electives from the B.S. requirement may count toward the fulfillment of the point requirement of the M.S. degree. Additional benefits include simplified application process, no GRE is required, and no reference letters are required. To qualify for this program, students must have a cumulative GPA of at least 3.4 and strong recommendations from within the Department. Students should apply for the program by April 30 in their junior year. For more information on requirements and access to an application form, please visit me.columbia.edu/integrated-bsms-program.

Express M.S. Application
The Express M.S. Application is offered to current seniors, including 3-2 students, who are enrolled in the BS program. In the Express M.S. Application, a master’s degree can be earned seamlessly. Graduate classes are available for seniors to apply toward their M.S. degree and the advanced courses that will be taken have been designed to have the exact prerequisites completed as an undergraduate. Other advantages include the opportunity for better course planning and creating a streamlined set of courses more possible. Additional benefits include simplified application process, no GRE is required and no reference letters are required. To qualify for this program, your cumulative GPA should be at least 3.5. For more information on requirements and access to an application, please visit me.columbia.edu/ms-express-application-1.

Barnard 4+1 Mechanical Engineering Pathways - Physics
The Barnard 4+1 Pathway in Physics is offered to current Barnard College juniors with a GPA of 3.5 or higher to apply to Master’s programs in Civil Engineering, Electrical Engineering, and Mechanical Engineering. Students should inquire with Beyond Barnard and plan on attending an introductory information sessions for the unique 4+1 Pathway they may be interested in pursuing.

Faculty contact at Barnard: Professor Reshmi Mukherjee, rmukherj@barnard.edu at SEAS: Professor Gerard Ateshian, gaa3@columbia.edu

GRADUATE PROGRAMS
The Department of Mechanical Engineering offers two doctoral degrees: Doctor of Philosophy (Ph.D.) and Doctor of Engineering Science (Eng.Sc.D.), and the Master of Science degree. The Ph.D. degree is conferred by the Graduate School of Arts and Science, and the Eng.Sc.D. degree is conferred by The Fu Foundation School of Engineering and Applied Science.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

Master of Science Degree Program
The program leading to the Master of Science degree in mechanical engineering requires completion of a minimum of 30 points of approved coursework consisting of no fewer than ten courses. A thesis based on either experimental, computational, or analytical research is optional and may be counted in lieu of up to 6 points of coursework. In general, attainment of the degree requires one academic year of full-time study, although it may also be undertaken on a part-time basis over a correspondingly longer period. A minimum grade-point average of 2.5 is required for graduation.

The M.S. degree in mechanical engineering requires a student to take a sequence of courses that shows a clearly discernible focus. In consultation with their adviser an M.S. student can develop a focus specifically tailored to their interests and objectives, and we refer to this as the standard track. Alternatively, M.S. students can pick from a set of predefined tracks.

Typical choices in the standard track include such subjects as mechanics of solids and fluids, thermodynamics, heat transfer, manufacturing engineering, robotics, kinematics, dynamics and vibrations, controls, and power generation. Nevertheless, the following guidelines must be adhered to:

1. All courses must be at the graduate level, i.e., numbered 4000 or higher, with at least two 6000-level lecture courses in SEAS. At least one of the 6000-level courses must be in Mechanical Engineering.
2. Every program must contain at least
one course in mathematics (APMA, MATH, STAT course designations) covering material beyond what the student has taken previously. It is recommended to be taken early in the sequence, in order to serve as a basis for the technical coursework. Alternatively, any one of the following courses may be taken to satisfy the math requirement: BMEN E4110 Biostatistics; COMS W4701 Artificial intelligence; COMS W4771 Machine learning; IEOR E4150* (same as STAT GU4001); MECE E4520 Data science for mechanical engineers; and ORCA E4500 Foundations of data science.

3. Out-of-department study is encouraged, but must be taken in consultation with a faculty adviser.

4. At least five courses must be in Mechanical Engineering.

Rather than selecting the standard option, students can select a concentration in either biomechanics, energy systems, micro/nanoscale engineering, or robotics and control. The requirements for a concentration are identical to those of the standard track, with one exception: students must take at least 15 points from a list determined by an adviser in consultation with an advisory committee. The currently available elective concentrations are listed below.

**M.S. in Mechanical Engineering with Concentration in Biomechanics**

Advisers: Professors Gerard Ateshian, Karen Kasza, Kristin Myers, and Vijay Vedula

The concentration in biomechanics is developed in coordination with the Department of Biomedical Engineering. It provides the M.S. candidate with knowledge of the mechanics of biological tissues. The 4000-level courses offered in this concentration provide foundations of fluid and solid mechanics applicable to biomechanics, as well as applications of mechanics to specific cell, tissue, and organ systems. The higher-level courses provide deeper foundations on theoretical and computational approaches relevant to biomechanics. This concentration is a suitable preparation for careers in the biomedical devices industry or engineering and scientific consulting.

To choose this concentration, select "Mechanical Engineering Biomechanics Master of Science" in the Program field when filling in the online application for the M.S. program. The name of this program will be listed on graduates’ transcripts.

Requirements: While satisfying the requirements for a Master of Science in Mechanical Engineering, take at least five courses from:

- MEBM E4703: Molecular mechanics in biology
- MEBM E4710: Morphogenesis: shape and structure in biological materials
- MECE E4100: Mechanics of fluids
- MECE E6100: Advanced mechanics of fluids
- MECE E6106: Finite element method for fluid flow and fluid-structure interactions
- MEBM E6310–E6311: Mixture theories for biological tissues I and II
- MECE E6422–E6423: Introduction to the theory of elasticity I and II
- MECE E8501: Advanced continuum biomechanics

When offered by the Biomedical Engineering Department, the following courses may also count toward the Biomechanics track:

- BMEN E4301: Structure, mechanics, and adaptation of bone
- BMEN E4302: Biomechanics of musculoskeletal soft tissues
- BMEN E4305: Cardiac mechanics
- BMEN E4310: Solid biomechanics
BMEN E4320: Fluid biomechanics
BMEN E4340: Biomechanics of cells
BMEN E4350: Biomechanics of developmental biology
BMEN E4570: Science and engineering of body fluids
BMEN E4750: Sound and hearing
BMEN E6301: Modeling of biological tissues with finite elements
BMME E4702: Advanced musculoskeletal biomechanics

One 3-credit research course can be counted toward the concentration if the research is approved by the student’s adviser and is biomechanics related.

M.S. in Mechanical Engineering with Concentration in Energy Systems
Advisers: Professors Michael Burke, Vijay Modi, and Arvind Narayanashwamy

The concentration in energy systems provides the M.S. candidate with a global understanding of current energy challenges. Advanced thermofluidic knowledge is provided to design and optimize energy systems, with a strong emphasis on renewable energies. Courses related to energy and environmental policy, two strong areas of Columbia as a global university, can be integrated into the course sequence. This specialization is a suitable preparation for careers in energy production and energy consultation.

Requirements: While satisfying the requirements for a Master of Science in Mechanical Engineering, take at least five courses from:

- MECE E4210: Energy infrastructure planning
- MECE E4211: Energy sources and conversion
- MECE E4302: Advanced thermodynamics
- MECE E4303: Turbomachinery
- MECE E4305: Mechanics and thermodynamics propulsion
- MECE E4312: Solar thermal engineering
- MECE E4314: Energy dynamics of green buildings
- MECH E4320: Intro to combustion
- MECE E4330: Thermofluid systems design
- MECE E6100: Advanced mechanics of fluids
- MECE E6104: Case studies in computational fluid dynamics
- MECE E6313: Advanced heat transfer
- EAEE E6126: Carbon sequestration

Furthermore, students must take one course in statistics (STAT or SIEO designations). One 3-credit research course can be counted toward the concentration if the research is approved by the student’s adviser and is energy related.

M.S. in Mechanical Engineering with Concentration in Micro/Nanoscale Engineering
Advisers: Professors James Hone, Jeffrey Kysar, and P. James Schuck

The concentration in micro/nanoscale engineering provides the M.S. candidate with an understanding of engineering challenges and opportunities in micro- and nanoscale systems. The curriculum addresses fundamental issues of mechanics, fluid mechanics, optics, heat transfer, and manufacturing at small-size scales. Application areas include MEMS, bio-MEMS, microfluidics, thermal systems, and carbon nanostructures.

Requirements: The requirements for the micro/nanoscale engineering track ensures that students obtain an education in micro/nanoscale engineering that is both broad and deep. Students will be required to take at least five classes from a selected pool that covers many aspects of micro/nanoengineering. Currently, eight classes are compatible with the general requirements for the Master of Science degree in Mechanical Engineering. These include:

- MECE E4058: Mechatronics
- MECE E4212: Microelectromechanical systems (MEMS)
- MECE E4213: BioMEMS
- MECE E4214: MEMS production and manufacturing
- MECE E6137: Nanoscale actuation and sensing
- MECE E6432: Small scale mechanical behavior

When offered by other departments, the following courses may also count toward the micro/nanoscale concentration:

- APPH E6081: Solid state physics 1
- ELEN E4106: Advanced solid state device materials
- ELEN E4411: Fundamentals of photonics
- ELEN E4944: Principles of device microfabrication
- ELEN E6331: Principles semiconductor physics
- ELEN E6414: Photonic integrated circuits
- ELEN E6945: Device nano fabrication
- MSAE E4090: Nanotechnology
- MSAE E4100: Crystallography
- PHYS W4018: Solid state physics

One 3-credit research course can be counted toward the concentration if the research is approved by the student’s adviser and is micro/nanoscale related.

M.S. in Mechanical Engineering with Concentration in Robotics and Control
Advisers: Professors Sunil Agrawal, Matei Ciocarlie, Hod Lipson, and Richard Longman

The field of robotics is seeing unprecedented growth, in areas as diverse as manufacturing, logistics, transportation, health care, space exploration, and more. This program prepares students for a career in robotics and its many applications in society. Students perform in-depth study of topics such as robotic manipulation, navigation, perception, human interaction, medical robotics, assistance and rehabilitation. This specialization is a suitable preparation for joining established companies, information-age dominant players investing heavily in this field, or the new wave of robotics start-ups aiming to provide disruptive innovations. Many of the acquired skills can be applied in other fields as diverse as automation, manufacturing, computer graphics or machine vision. This program can also be a foundation for a research career in robotics and related areas, in both academia and industry.

Requirements: While satisfying the requirements for a Master of Science in Mechanical Engineering, take at least five courses from:

- MECE E4058: Mechatronics and embedded microcomputer control
- MECE E4602: Intro to robotics
- MECE E4606: Digital manufacturing
- MECE E4611: Robotics studio
- MECE E6400: Advanced machine dynamics
- MECE E6614: Advanced topics in robotics and mechanism synthesis
- MECS E4510: Design automation
- MECS E6615: Robotic manipulation
- MECS E6616: Robot learning
- EEME E4601: Digital control systems
- EEME E6601: Introduction to control theory
- EEME E6602: Modern control theory
- EEME E6610: Optimal control theory
- ELEN E4810: Digital signal processing
- BMME E4702: Advanced musculoskeletal biomechanics

When offered by the Computer Science Department, these courses may
also be used to satisfy the robotics requirements:

COMS W4731: Computer vision
COMS W4733: Computational aspects of robotics
COMS E6733: 3D photography

One 3-credit research course can be counted toward the concentration if the research is approved by the student’s adviser and is robotics related.

**Doctoral Degree Program**

All applications to the doctoral program in mechanical engineering are administered by The Fu Foundation School of Engineering and Applied Science. Students who matriculate into the doctoral program without a master’s degree earn a Master of Science degree while pursuing their doctoral degree.

Doctoral candidates are expected to attain a level of mastery in an area of mechanical engineering and must therefore choose a field and take the most advanced courses offered in that field. Candidates are assigned a faculty adviser whose task is to help choose a program of courses, provide general advice on academic matters, and monitor academic performance. Candidates also choose a faculty member in the pertinent area of specialization to serve as their research adviser. This adviser helps select a research problem and supervises the research, writing, and defense of the dissertation.

**Program Requirements**

- 30 credits beyond master’s degree
- GPA of 3.2 or better in graduate courses
- 4 semesters of graduate seminar MECE E9500
- Completion of all milestones

See www.me.columbia.edu/academics/doctoral-program for more information.

**COURSES IN MECHANICAL ENGINEERING**

**MECE E1001x Mechanical engineering: micromachines to jumbo jets**
3 pts. Lect: 3. Not offered in 2022–2023
Corequisite(s): MATH UN1101 Calculus I. The role of Mechanical Engineering in developing many of the fundamental technological advances on which today’s society depends. Topics include airplanes, automobiles, robots, modern manufacturing methods as well as the emerging fields of microelectromechanical machines (MEMS) and nanotechnology. The physical concepts that govern the operation of these technologies will be developed from basic principles and then applied in simple design problems. Students will also be exposed to state-of-the-art innovations in each case study.

**MECE E1008x or y Introduction to machining**
1 pt. Instructor to be announced.
Introduction to the manual machine operation, CNC fabrication and usage of basic hand tools, band/hack saws, drill presses, grinders and sanders.

**MECE E1304x or y Naval ship systems, I**
Students are strongly advised to consult with the ME Department prior to registering for this course. A study of ship characteristics and types including ship design, hydrodynamic forces, stability, compartmentation, propulsion, electrical and auxiliary systems, interior communications, ship control, and damage control; theory and design of steam, gas turbine, and nuclear propulsion; shipboard safety and firefighting. This course is part of the Naval ROTC program at Columbia but will be taught at SUNY Maritime. Enrollment may be limited; priority is given to students participating in Naval ROTC. Will not count as a technical elective. Students should see a faculty adviser as well as Columbia NROTC staff (nrotc@columbia.edu) for more information.

**MECE E3018x Mechanical engineering laboratory, I**
3 pts. Lect: 3. Professor Yesilevskiy.

**MECE E3028y Mechanical engineering laboratory, II**
3 pts. Lect: 3. Professor Lin.
Experiments in engineering and physical phenomena: aerofoil lift and drag in wind tunnels, laser Doppler anemometry in immersed fluidic channels, supersonic flow and shock waves, Rankine thermodynamical cycle for power generation, and structural truss mechanics and analysis.

**MECE E3038x Mechanical engineering laboratory, III**
Mechatronic control of mechanical and electromechanical systems. Control of various thermodynamic cycles, including internal combustion engine (Otto cycle). Reverse engineering of an electromechanical product.

**MECE E3100x Introduction to mechanics of fluids**
3 pts. Lect: 3. Professor Kasza.

**ENME E3105x and y Mechanics**
Prerequisite(s): PHYS UN1401 and MATH UN1101, UN1102, and UN1201 or APMA E2000. Elements of statics, dynamics of a particle, and systems of particles.

**ENME E3113x Mechanics of solids**
3 pts. Lect: 3. Professor Belbi.

**MECE E3301x Thermodynamics**
3 pts. Lect: 3. Professor Burke or Narayanaswamy.
Classical thermodynamics. Basic properties and concepts, thermodynamic properties of pure substances, equation of state, work, heat, the first and second laws for flow and nonflow processes, energy equations, entropy, and irreversibility. Introduction to power and refrigeration cycles.

**MECE E3311y Heat transfer**
3 pts. Lect: 3. Professor Burke or Narayanaswamy.

**MECE E3401x Mechanics of machines**
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): ENME E3105 and MECE E3408. Introduction to mechanisms and machines, analytical and graphical synthesis of mechanism, displacement analysis, velocity analysis, acceleration analysis of linkages, dynamics of mechanism, cam design, gear and gear trains, and computer-aided mechanism design.

**MECE E3408x and y Computer graphics and design**
3 pts. Lect: 3. Professor Vukelic.
Introduction to drafting, engineering graphics, computer graphics, solid modeling, and mechanical engineering design. Interactive computer graphics and numerical methods applied to the solution of mechanical engineering design problems.

**MECE E3409x Machine design**
3 pts. Lect: 3. Professor Yesilevskiy.
Prerequisite(s): MECE E3408. Computer-aided analysis of general loading states and deformation
of machine components using singularity functions and energy methods. Theoretical introduction to static failure theories, fracture mechanics, and fatigue failure theories. Introduction to conceptual design and design optimization problems. Design of machine components such as springs, shafts, fasteners, lead screws, rivets, welds. Modeling, analysis, and testing of machine assemblies for prescribed design problems. Problems will be drawn from statics, kinematics, dynamics, solid modeling, stress analysis, and design optimization.

**MECE E3411y Fundamentals of engineering**

Prerequisite(s): Senior standing. Review of core courses in mechanical engineering, including mechanics, strength of materials, fluid mechanics, thermodynamics, heat transfer, materials and processing, control, and mechanical design and analysis. Review of additional topics, including engineering economics and ethics in engineering. The course culminates with a comprehensive examination, similar to the Fundamentals of Engineering examination. Meets the first 4.5 weeks only.

**MECE E3414x Mechanics of solids for mechanical engineers**

Prerequisite(s): Mechanics, linear algebra, ordinary differential equations. Introduction to the mechanics of solids with an emphasis on mechanical engineering applications. Stress tensor, principal stresses, maximum shear stress, stress equilibrium, infinitesimal strain tensor, Hooke’s law, boundary conditions. Introduction to the finite element method for stress analysis. Static failure theories, safety factors, fatigue failure. Assignments include finite element stress analyses using university-provided commercial software.

**MECE E3420x Engineering design—concept/design generating**

3 pts. Lect: 3. Professor Yesilevskiy.
Prerequisite(s): Senior standing. Corequisite(s): MECE E3409. A preliminary design for an original project is a prerequisite for the capstone design course. Will focus on the steps required for generating a preliminary design concept. Included will be a brainstorming concept generation phase, a literature search, incorporation of multiple constraints, adherence to appropriate engineering codes and standards, and the production of a layout drawing of the proposed capstone design project in a Computer Aided Design (CAD) software package. Note: MECE students only.

**MECE E3430y Engineering design**

Prerequisite(s): MECE E3420. Building on the preliminary design concept, the detailed elements of the design process are completed: systems synthesis, design analysis optimization, incorporation of multiple constraints, compliance with appropriate engineering codes and standards, and Computer Aided Design (CAD) component part drawings. Execution of a project involving the design, fabrication, and performance testing of an actual engineering device or system.

**MECE E3450x or y Computer-aided design**

3 pts. Lect: 3. Professor Ateshian.
Prerequisite(s): ENME E3105, E3113, MECE E3408, E3311. Introduction to numerical methods and their applications to rigid body mechanics for mechanisms and linkages. Introduction to finite element stress analysis for deformable bodies. Computer-aided mechanical engineering design using established software tools and verifications against analytical and finite difference solutions.

**EEME E3601x Classical control systems**

3 pts. Lect: 3. Professor Longman.
Prerequisite(s): MATH UN2030. Analysis and design of feedback control systems. Transfer functions; block diagrams; proportional, rate, and integral controllers; hardware, implementation. Roouth stability criterion, root locus, Bode and Nyquist plots, compensation techniques.

**MECE 3610y Materials and processes in manufacturing**

3 pts. Lect: 3. Professor Yao.
Prerequisite(s): ENME E3113 or the equivalent. Introduction to microstructures and properties of metals, polymers, ceramics and composites; typical manufacturing processes: material removal, shaping, joining, and property alteration; behavior of engineering materials in the manufacturing processes.

**MECE E3900x-E3901y Honors tutorial in mechanical engineering**

3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): 3.2 or higher GPA. Individual study; may be selected after the first term of the junior year by students maintaining a 3.2 grade-point average. Course format may vary from individual tutorial to laboratory work to seminar instruction under faculty supervision. Projects requiring machine-shop use must be approved by the laboratory supervisor. Students may count up to 6 points toward degree requirements. Students must submit both a project outline prior to registration and a final project write up at the end of the semester.

**MECE E3998x and y Projects in mechanical engineering**

1–3 pts. Members of the faculty.
Prerequisite(s): Approval by faculty member who agrees to supervise the work. Independent project involving theoretical, computational, experimental, or engineering design work. May be repeated, but no more than 3 points may be counted toward degree requirements. Projects requiring machine-shop use must be approved by the laboratory supervisor. Students must submit both a project outline prior to registration and a final project write-up at the end of the semester.

**MECE E4058x and y Mechatronics and embedded microcomputer control**

3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): ELEN E1201. Recommended: ELEN E3000. Enrollment limited to 12 students. Mechatronics is the application of electronics and microcomputers to control mechanical systems. Systems explored include on/off systems, solenoids, stepper motors, DC motors, thermal systems, magnetic levitation. Use of analog and digital electronics and various sensors for control. Programming microcomputers in Assembly and C. Lab required.

**MECE E4078x or y Internet of (Mechanical) Things**

3 pts. Lect: 3. Hands-on, project-oriented course covering foundations of Internet of Things (IoT) technologies as they relate to the physical world. Projects utilizing Arduino and Raspberry Pi platforms. End-to-end IoT including sensors, basic controls, embedded systems programming, networking, IoT protocols, power consumption/optimization, and cloud connectivity. Build real IoT devices and systems in two team-based projects.

**MECE E4100y Mechanics of fluids**

3 pts. Lect: 3. Professor Kazma.
Prerequisite(s): MECE E3100 or equivalent. Fluid dynamics and analyses for mechanical engineering and aerospace applications: boundary layers and lubrication, stability and turbulence, and compressible flow. Turbomachinery as well as additional selected topics.

**IEME E4200x or y Introduction to human-centered design**

1.5 pts. Lect: 4.5. Fast-paced introduction to human-centered design. Students learn the vocabulary of design methods, understanding of design process. Small group projects to create prototypes. Design of simple product, more complex systems of products and services, and design of business.

**MECE E4210x or y Energy infrastructure planning**

3 pts. Lect: 3. Professor Modi.
Prerequisite(s): One year each of college level physics, chemistry, and mathematics. Energy infrastructure planning with specific focus on countries with rapidly growing infrastructure needs. Spatiotemporal characteristics, scale, and environmental footprints of energy resources, power generation and storage, modeling demand growth, technology choices and learning for planning. Computer-assisted decision support and network design/optimization tools. Similarities, differences and interactions among electricity.
gas, information, transportation and water distribution networks. Penetration of renewable and/or decentralized technologies into existing or new infrastructure. Special guest lectures on infrastructure finance, regulation and public-private partnerships.

**MECE E4211x or y Energy: sources and conversion**
3 pts. Lect: 3. Professor Modi.
Prerequisite(s): MECE E3301. Energy sources such as oil, gas, coal, gas hydrates, hydrogen, solar, and wind. Energy conversion systems for electrical power generation, automobiles, propulsion and refrigeration. Engines, steam and gas turbines, wind turbines; devices such as fuel cells, thermoelectric converters, and photovoltaic cells. Specialized topics may include carbon-dioxide sequestration, cogeneration, hybrid vehicles and energy storage devices.

**MECE E4212x or y Microelectromechanical systems**
3 pts. Lect: 1.5. Lab: 3. Professor Schuck.
MEMS markets and applications; scaling laws; silicon as a mechanical material; Sensors and actuators; micromechanical analysis and design; substrate (bulk) and surface micromachining; computer aided design; packaging; testing and characterization; microfluidics.

**MECE E4213x or y Biomicroelectromechanical systems (BioMEMS): design, fabrication, and analysis**
3 pts. Lect: 3. Professor Lin.
Prerequisite(s): MECE E3100 and E3311, course in transport phenomena, or instructor’s permission. Silicon and polymer micro/nanofabrication techniques; hydrodynamic microfluidic control; electrokinetic microfluidic control; microfluidic separation and detection; sample preparation; micro bioreactors and temperature control; implantable MEMS, including sensors, actuators and drug delivery devices.

**MECE E4214x or y MEMS production and packaging**
3 pts. Lect: 3. Professor Hilton.
Prerequisite(s): MECE E4212. Applications-driven study of the packaging and manufacturing of MEMS devices. Covers underlying physical phenomena such as fracture mechanics and materials science topics relevant to MEMS production. Packaging approaches such as glass-to-metal seals and CTE matching. Electrical filtering and noise sources as relevant to the transducer signal chain. Comparative MEMS design as focused on a common example: pressure transducers.

**MECE E4302x Advanced thermodynamics**
3 pts. Lect: 3. Professor Burke.
Prerequisite(s): MECE E3301. Advanced classical thermodynamics. Availability, irreversibility, generalized behavior, equations of state for nonideal gases, mixtures and solutions, phase and chemical behavior, combustion. Thermodynamic properties of ideal gases. Applications to automotive and aircraft engines, refrigeration and air conditioning, and biological systems.

**MECE E4304x Turbomachinery**
Introduces the basics of theory, design, selection and applications of turbomachinery. Turbomachines are widely used in many engineering applications such as energy conversion, power plants, air-conditioning, pumping, refrigeration and vehicles engines, as there are pumps, blowers, compressors, gas turbines, jet engines, wind turbines, etc. Applications are drawn from energy conversion technologies, HVAC and propulsion. Provides a basic understanding of the different kinds of turbomachines.

**MECE E4305y Mechanics and thermodynamics of propulsion**
3 pts. Lect: 3. Professor Bradshaw.
Prerequisite(s): MECE E3301x Thermodynamics and MECE E3311y Heat transfer; MECE E4304x Turbomachinery (or instructor approval). Principles of propulsion. Thermodynamic cycles of air breathing propulsion systems including ramjet, scramjet, turbojet, and turbofan engine and rocket propulsion system concepts. Turbine engine and rocket performance characteristics. Component and cycle analysis of jet engines and turbomachinery. Advanced propulsion systems. Columbia Engineering interdisciplinary course.

**MECE E4306x y Introduction to aerodynamics**
3 pts. Lect: 3. Professor Levoci.
Principles of flight, incompressible flows, compressible regimes. Inviscid compressible aerodynamics in nozzles (wind tunnels, jet engines), around wings (aircraft, space shuttle) and around blunt bodies (rockets, reentry vehicles). Physics of normal shock waves, oblique shock waves, and explosion waves.

**IEME E4310x The manufacturing enterprise**
The strategies and technologies of global manufacturing and service enterprises. Connections between the needs of a global enterprise, the technology and methodology needed for manufacturing and product development, and strategic planning as currently practiced in industry.

**MECE E4312x Solar thermal engineering**
3 pts. Lect: 3. Professor Naraghi.

**MECE E4313x Decarbonizing buildings studio: energy system retrofits at speed and scale**
3 pts. Lect: 3. Instructor to be announced.
Historical co-evolution of building energy systems and fuels. Classifying existing buildings into typologies that are a prevalent combination of building size, age, fuels, equipment, distribution and zoning controls. Fuels, electricity, furnaces, boilers, heat pumps. Overview of common heat and hot water distribution systems. Case-study based approach to evaluate retrofit options for each typology. Considerations of location, staging upgrades, envelope efficiency, retrofit cost structure, paybacks with a view toward decarbonization.

**MECE E4314y Energy dynamics of green buildings**
3 pts. Lect: 3. Professor Naraghi.

**MECH E4320x Introduction to combustion**
3 pts. Lect: 3. Professor Burke.
Prerequisite(s): Introductory thermodynamics, fluid dynamics, and heat transfer at the undergraduate level or instructor’s permission. Thermodynamics and kinetics of reacting flows; chemical kinetic mechanisms for fuel oxidation and pollutant formation; transport phenomena; conservation equations for reacting flows; laminar premixed flames (including droplet vaporization and burning); laminar premixed flames; flame stabilization, quenching, ignition, extinction, and other limit phenomena; detonations; flame aerodynamics and turbulent flames.
MECE E4404x or y Tribology: friction, lubrication, and wear
Prerequisite(s): MECE E3100, E3311, and ENME E3113, or permission of the instructor. Friction, lubrication, and wear between sliding surfaces. Surface metrology, contact mechanics, and sliding friction. Deformation, wear, and temperature rise of nonlubricated, liquid-lubricated, and solid-lubricated rolling and sliding materials. The theories of boundary, elastohydrodynamic, hydrodynamic, hydrostatic, and solid-phase lubrication. Lubricant flow and load-carrying capacity in bearings. Special applications such as gear trains, cam/tappets, and micro- and nanoscale tribological interfaces.

MECE E4430x Automotive dynamics
3 pts. Lect: 3. Professor Browne.
Prerequisite(s): ENME E3105 or equivalent; Recommended: ENME E3100 or E3106. Reviews fundamentals of vehicle dynamics. A systems-based engineering approach to explore areas of: tire characteristics, aerodynamics, stability and control, wheel loads, ride and roll rates, suspension geometry, and dampers. A high-performance vehicle (racecar) platform used as an example to review topics.

MECE E4431x or y Space vehicle dynamics
3 pts. Lect: 3. Professor Longman.
Prerequisite(s): ENME E3105; ENME E4202 recommended. Space vehicle dynamics and control, rocket equations, satellite orbits, initial trajectory designs from Earth to other planets, satellite attitude dynamics, gravity gradient stabilization of satellites, spin-stabilized satellites, dual-spin satellites, satellite attitude control, modeling, dynamics, and control of large flexible spacecraft.

MEBM E4439x Modeling and identification of dynamic systems
Prerequisite(s): APMA E2101, ELEN E3801, or corequisite(s) EEME E3601, or permission of instructor. Generalized dynamic system modeling and simulation. Fluid, thermal, mechanical, diffusive, electrical, and hybrid systems are considered. Nonlinear and high order systems. System identification problem and Linear Least Squares method. State-space and noise representation. Kalman filter. Parameter estimation via prediction error and subspace approaches. Iterative and bootstrap methods. Fit criteria. Wide applicability: medical, energy, others. MATLAB and Simulink environments.

MECE E4440x or y Optimization of dynamic systems
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): Course on linear and/or nonlinear control theory, introduction to Robotics, or instructor's permission. Fundamentals for optimizing performance of dynamic systems described by a set of ordinary differential equations based on theory of variational calculus. Systematic methods to solve optimization problems using numerical methods. Topics include: Static Optimization of systems with equality and inequality and inequal-

MECE E450f y Geometrical modeling
Prerequisite(s): COMS W1005. Relationship between 3D geometry and CAD/CAM; representations of solids; geometry as the basis of analysis, design, and manufacturing; constructive solid geometry and the CSG tree; octree representation and applications; surface representations and intersections; boundary representation and boundary evaluation; applied computational geometry; analysis of geometrical algorithms and associated data structures; applications of geometrical modeling in vision and robotics.

MECE E4502x Computational geometry for CAD/CAM
Prerequisite(s): COMS W1005 FORTRAN or PASCAL. Analysis of geometric problems and the design of efficient methodologies to obtain solutions to these problems. Algorithms to be studied include geometric searching, convex hulls, triangulations, Voronoi diagrams, intersections, hidden surfaces. Emphasis will be on practical aspects of these algorithms, and on applications of the solutions in computer-aided product design and manufacturing.

MECS E4603x Applied robotics: algorithms and software
Prerequisite(s): Fundamental programming skills (e.g., COMS W1002, W1004, W1005, ENGI E1006, or equivalent). Science and systems aspects of Robotics from applied perspective, focusing on algorithms and software tools. Spatial reasoning; tools for manipulating and visualizing spatial relationships. Analysis of robotic manipulators; numerical methods for kinematic analysis. Motion planning, search-based and stochastic approaches. Applications for force and impedance control. Grading based on combination of exams and projects implemented using Robot Operating System (ROS) software framework and executed on real and simulated robotic manipulators.

MECE E4604x Product design for manufacturability
Prerequisite(s): Manufacturing process, computer graphics, engineering design, mechanical design. General review of product development process; market analysis and product system design; principles of design for manufacturing; strategy for material selection and manufacturing process choice; component design for machining; casting; molding; sheet metal working and inspection; general assembly processes; product design for manual assembly; design for robotic and automatic assembly; case studies of product design and improvement.

MECE E4606y Digital control systems
3 pts. Lect: 3. Professor Beigi.
Prerequisite(s): EEME E3601 or ELEN E3201.

MECE E4602x Introduction to robotics
3 pts. Lect: 3. Professor Ciocarlie or Agrawal.
Overview of robot applications and capabilities. Linear algebra, kinematics, statics, and dynamics of robot manipulators. Survey of sensor technology: force, proximity, vision, compliant manipulators. Motion planning and artificial intelligence; manipulator programming requirements and languages.
ed design, and mechanical design or instructor's permission. Computer-aided design, free-form surface modeling, tooling and fixtureing, computer numeric control, rapid prototyping, process engineering, fixed and programmable automation, industrial robotics.

MECE E4610x Advanced manufacturing processes
3 pts. Lect: 3. Professor Yao.
Prerequisite(s): Introductory course on manufacturing processes, and heat transfer, knowledge of engineering materials, or instructor's permission. Principles of nontraditional manufacturing, nontraditional transport and media. Emphasis on laser assisted materials processing, laser material interactions with applications to laser material removal, forming, and surface modification. Introduction to electrochemical machining, electrical discharge machining and abrasive water jet machining.

MECE E4611x or y Robotics studio
Prerequisite(s): Knowledge of basic computer programming (e.g., Java, Matlab, Python) or instructor's permission. Hands-on studio class exposing students to practical aspects of the design, fabrication, and programming of physical robotic systems. Students experience entire robot creation process, covering conceptual design, detailed design, simulation and modeling, digital manufacturing, electronics and sensor design, and software programming.

MECE E4612x or y Sustainable manufacturing processes
3 pts. Lect: 3. Professor Yao.
Prerequisite(s): Introductory course in engineering materials and manufacturing processes or instructor's permission. Fundamentals of sustainable design and manufacturing, metrics of sustainability, analytical tools, principles of life cycle assessment, manufacturing tools, processes and systems, energy assessment and minimization in manufacturing, sustainable manufacturing automation, sustainable manufacturing systems, remanufacturing, recycling and reuse.

BMME E4702x Advanced musculoskeletal biomechanics
Advanced analysis and modeling of the musculoskeletal system. Topics include advanced concepts of 3D segmental kinematics, musculoskeletal dynamics, experimental measurements of joints kinematics and anatomy, modeling of muscles and locomotion, multibody joint modeling, introduction to musculoskeletal surgical simulations.

MEBM E4703x Molecular mechanics in biology
Prerequisite(s): ENME E3105, APMA E2101, or instructor's permission. Mechanical understanding of biological structures including proteins, DNA and RNA in cells and tissues. Force response of proteins and DNA, mechanics of membranes, biophysics of molecular motors, mechanics of protein-protein interactions. Introduction to modeling and simulation techniques, and modern biophysical techniques such as single molecule FRET, optical traps, AFM, and superresolution imaging, for understanding molecular mechanics and dynamics.

MEBM E4710x or y Morphogenesis: shape and structure in biological materials
Prerequisite(s): Courses in mechanics, thermodynamics, and ordinary differential equations at the undergraduate level or instructor's permission. Introduction to how shape and structure are generated in biological materials using engineering approach emphasizing application of fundamental physical concepts to a diverse set of problems. Mechanisms of pattern formation, self-assembly, and self-organization in biological materials, including intracellular structures, cells, tissues, and developing embryos. Structure, mechanical properties, and dynamic behavior of these materials. Discussion of experimental approaches and modeling. Course uses textbook materials as well as collection of research papers.

MEIE E4810y Introduction to human spaceflight
3 pts. Lect: 3. Professor Massimino.
Prerequisite(s): Department permission and knowledge of MATLAB or equivalent. Introduction to human spaceflight from a systems engineering perspective. Historical and current space programs and spacecraft. Motivation, cost, and rationale for human space exploration. Overview of space environment needed to sustain human life and health, including physiological and psychological concerns in space habitat. Astronaut selection and training processes, spacewalking, robotics, mission operations, and future program directions. Systems integration for successful operation of a spacecraft. Highlights from current events and space research, Space Shuttle, Hubble Space Telescope, and International Space Station (ISS). Includes a design project to assist International Space Station astronauts.

MECE E4811x Aerospace human factors engineering
3 pts. Lect: 2.5. Professor Massimino.
Prerequisite(s): Instructor's permission. Engineering fundamentals and experimental methods of human factors design and evaluation for spacecraft which incorporate human-in-the-loop control. Develop understanding of human factors specific to spacecraft design with human-in-the-loop control. Design of human factors experiments utilizing task analysis and user testing with quantitative evaluation metrics to develop a safe and high-performing operational space system. Human-centered design, functional allocation and automation, human sensory performance in the space environment, task analysis, human factors experimental methods and statistics, space vehicle displays and controls, situation awareness, workload, usability, manual piloting and handling qualities, human error analysis and prevention, and anthropometrics.

MECE E4990x or y Special topics in mechanical engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Permission of the instructor. Topics and instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

MECE E4998x and y M.S. projects in mechanical engineering
1–3 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Master's level independent project involving theoretical, computational, experimental, or engineering design work. May be repeated, subject to Master's Program guidelines. Students must submit both a project outline prior to registration and a final project write-up at the end of the semester.

MECE E4999x and y Fieldwork
1 pt. Professor Lipson.
Prerequisite(s): Instructor's written permission. Only for ME graduate students who need relevant off-campus work experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed study program. Final reports required. May not be taken for pass/fail credit or audited. International students must consult with the International Students and Scholars Office.

MECE E6100x Advanced mechanics of fluids
3 pts. Lect: 3. Professor Aleshin.
Prerequisite(s): MATH UN2030 and MECE E3100. Eulerian and Lagrangian descriptions of motion. Stress and strain rate tensors, vorticity, integral and differential equations of mass, momentum, and energy conservation. Potential flow.

MECE E6102x or y Computational heat transfer and fluid flow
3 pts. Lect: 3. Professor Demetriou.

MECE E6103x Compressible flow
Prerequisite(s): APMA E4200, MECE E3100 and E3301. Fundamental analysis of compressible flows and its applications for various sonic/supersonic elements including supersonic airfoils/projectiles, nozzles, and shock tubes. Steady and unsteady shock/expansion waves, oblique shock waves. Shock reflections, methods of characteristic.

MECE E6104x Case studies in computational fluid dynamics
3 pts. Lect: 3. Professor Bilson.
Prerequisite(s): APAM E4200 and MECE E6100. Corequisite(s): APAM E4300 and MECE E4400. Hands-on case studies in computational fluid dynamics, including steady and transient flows, heat and mass transfer, turbulence, compressible flow and multiphase flow. Identifying assump-
tions, computational domain selection, model creation and setup, boundary conditions, choice of convergence criteria, visualization and interpretation of computed results. Taught in the Mechanical Engineering Computer Laboratory with Computational Fluid Dynamics software.

**MECE E6105y** Transport phenomena in the presence of interfaces
Prerequisite(s): MECE E3301 Thermodynamics and MECE E3311 Heat transfer; MECE E4100 Mechanics of fluids, or equivalent or instructor’s permission; CHEE E4252 Introduction to surface and colloid chemistry, or the equivalent, or the instructor’s permission. Surface energy and capillary phenomena. Wetting and spreading of liquids, wetting line pinning and hysteresis, dynamics of wetting. Surfactants. Bubbles: nucleation, stability, dynamics, microstreaming. Jets and Drops: generation, dynamics, stability and impact with surfaces. Measurement of transport phenomena involving interfaces. Interfacial transport phenomena involving thermal, chemical or electrical gradients. Applications in microfluidic systems.

**MECE E6106x** Finite element method for fluid flow and fluid-structure interactions
3 pts. Lect: 3. Professor Vedula.
Prerequisite(s): MECE E4100 or E6100, ENME E4332, or equivalents, or instructor’s permission and high-level programming language (Fortran, C, C++, Python, MATLAB, etc.). Solving convection-dominated phenomena using finite element method (FEM), including convection-diffusion equation, Navier-Stokes, equation for incompressible viscous flows, and nonlinear fluid-structure interactions (FSI). Foundational concepts of FEM include function spaces, strong and weak forms, Galerkin FEM, isoparametric discretization, stability analysis, and error estimates. Mixed FEM for Stokes flow, incompressibility and inf-sup conditions. Stabilization approaches, including residue-based variational multiscale methods. Arbitrary Lagrangian-Eulerian (ALE) formulation for nonlinear FSI, and selected advanced topics of research interest.

**MECE E6137x or y** Nanoscale actuation and sensing
3 pts. Lect: 3. Professor Schuck.
Prerequisite(s): PHYS UN1402 or UN1602 or equivalent, or instructor’s permission. Interaction of light with nanoscale materials and structures for purpose of inducing movement and detecting small changes in strain, temperature, and chemistry within local environments. Methods for concentrating and manipulating light at length scales below the diffraction limit. Plasmonics and metamaterials, as well as excitons, phonons, and polaritons and their advantages for mechanical and chemical sensing, and controlling displacement at nanometer length scales. Applications to nanophotonic devices and recently published progress in nanomechanics and related fields.

**MECE E6200y** Turbulence

**MEBM E6310x–E6311y** Mixture theories for biological tissues, I and II
Prerequisite(s): MECE E6422 and APMA E4200 or equivalent. Development of governing equations for mixtures with solid matrix, interstitial fluid, and ion constituents. Formulation of constitutive models for biological tissues. Linear and nonlinear models of fibrillar and viscoelastic porous matrices. Solutions to special problems, such as confined and unconfined compression, permeation, indentation and contact, and swelling experiments.

**MECE E6313x** Advanced heat transfer
3 pts. Lect: 3. Professor Narayananswamy.
Prerequisite(s): MECE E3311. Corequisite(s): MECE E6100. Application of analytical techniques to the solution of multidimensional steady and transient problems in heat conduction and convection. Lumped, integral, and differential formulations. Topics include use of sources and sinks, laminar/turbulent forced convection, and natural convection in internal and external geometries.

**MECE E6320x or y** Multiscale phenomena in gases
Prerequisite(s): Knowledge of advanced thermodynamics (e.g., MECE E4302), or combustion (e.g., MECH E4320), or instructor’s permission. Gaseous phenomena from a molecular to macroscopic perspective. Quantum mechanics, statistical thermodynamics, nonequilibrium statistical mechanics, reaction rate theories, master equation, reaction processes, kinetic theory, equations of state, transport theories, and kinetic-transport equations. Applications to combustion, aerospace gas dynamics, and high-frequency sound propagation.

**MECE E6400y** Advanced machine dynamics
3 pts. Lect: 3. Professor Chbat.
Prerequisite(s): MECE E3401. Review of classical dynamics, including Lagrange’s equations. Analysis of dynamic response of high-speed machine elements and systems, including mass-spring systems, cam-follower systems, and gearing; shock isolation; introduction to gyrodynamics.

**MECE E6422x–E6423y** Introduction to the theory of elasticity, I and II
3 pts. Lect: 3. Professor Myers.
Corequisite(s): APMA E4200. Analysis of stress and strain. Formulation of the problem of elastic equilibrium. Torsion and flexure of prismatic bars. Problems in stress concentration, rotating disks, shrink fits, and curved beams; pressure vessels, contact and impact of elastic bodies, thermal stresses, propagation of elastic waves.

**MECE E6424x** Vibrations in machines, I
3 pts. Lect: 3. Instructor to be announced.

**MEEM E6432y** Small-scale mechanical behavior
Prerequisite(s): ENME E3113 or equivalent; APMA E4200 or equivalent. Mechanics of small-scale materials and structures require nonlinear kinematics and/or nonlinear stress vs. strain constitutive relations to predict mechanical behavior. Topics include variational calculus, deformation and vibration of beam, strings, plates, and membranes; fracture, delamination, bulging, buckling of thin films, among others. Thermodynamics of solids will be reviewed to provide the basis for a detailed discussion of nonlinear elastic behavior as well as the study of the equilibrium and stability of surfaces.

**EEME E6601x** Introduction to control theory
3 pts. Lect: 3. Professor Longman.
Prerequisite(s): MATH UN2030. A graduate-level introduction to classical and modern feedback control that does not presume an undergraduate background in control. Scalar and matrix differential equation models and solutions in terms of state transition matrices. Transfer functions and transfer function matrices, block diagram manipulations, closed loop response. Proportional, rate, and integral controllers, and compensators. Design by root locus and frequency response. Controllability and observability. Luenberger observers, pole placement, and linear-quadratic cost controllers.

**EEME E6602y** Modern control theory
Prerequisite(s): EEME E6601 or E4601 or ELEN E6201, or instructor’s permission. Singular value decomposition. ARX model and state space model system identification. Recursive least squares filters and Kalman filters. LQR, Hlinear model system identification. Recursive least squares filters and Kalman filters. LQR, Hlinear model system identification. Recursive least squares filters and Kalman filters. LQR, Hlinear model system identification. Recursive least squares filters and Kalman filters. LQR, Hlinear model system identification.
MECE E6614x or y Advanced topics in robotics and mechanism synthesis
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): APMA E2101, E3101, MECE E4602 (or COMS W4733). Recommended: MECE E3401 or instructor’s permission. Kinematic modeling methods for serial, parallel, redundant, wire-actuated robots and multifingered hands with discussion of open research problems. Introduction to screw theory and line geometry tools for kinematics. Applications of homotopy continuation methods and symbolic-numerical methods for direct kinematics of parallel robots and synthesis of mechanisms. Course uses textbook materials as well as a collection of recent research papers.

MECE E6615x or y Robotic manipulation: sensing, planning, design, and execution
3 pts. Lect: 3. Professor Ciocarlie.
Prerequisite(s): MECE E4602 or COMS W4733.
Theory and mechanisms of robotic manipulation, from sensor data, reasoning, and planning to implementation and execution. Grasp quality measures and optimization; planning and execution for manipulation primitives; sensor modalities: vision, touch, and proprioception; simulation for manipulation planning; design of robot manipulators. Grading based on a combination of class presentations of novel research results in the field, participation in discussions, and course projects combining simulation, processing of sensor data, planning for manipulation, design, and implementation on real robot hands.

MECS E6616x or y Robot learning
3 pts. Lect: 3. Professor Ciocarlie.

MECE E6617y Advanced kinematics, dynamics and control in robotics
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): Course on linear and/or nonlinear control theory, Introduction to Robotics, or instructor’s permission. Advanced topics in robotics using fundamentals of kinematics, dynamics, and control. Topics include: characterization of orientation and angular velocity of rigid bodies, kinematic solutions of planar mechanisms, dynamics of closed chains and free-floating bodies, gravity balancing of mechanism, dynamics and dependence of inertia redistribution, under-actuation systems, feedback linearization of SISO systems, feedback linearization of MIMO systems, design of under-actuated open-chain robots, parallel-actuated robots.

MECE E6620x or y Applied signal recognition and classification
3 pts. Lect: 3. Professor Beigi.
Prerequisite(s): MATH UN2030, APMA E3101, knowledge of a programming language, or permission of instructor. Applied recognition and classification of signals using a selection of tools borrowed from different disciplines. Applications include human biometrics, imaging, geophysics, machinery, electronics, networking, languages, communications, and finance. Practical algorithms are covered in signal generation, modeling, feature extraction, metrics for comparison and classification, parameter estimation, supervised, unsupervised and hierarchical clustering and learning, optimization, scaling and alignment, signals as codes emitted from natural sources, information, and extremely large-scale search techniques.

MECE E6700x Carbon nanotube science and technology
3 pts. Lect: 3. Professor Schuck.
Prerequisite(s): Knowledge of introductory solid-state physics (e.g., PHYS GU4018, APHP E6081, or MSAE E3103) or instructor’s permission. Basic science of solid-state systems. Crystal structure, electronic and phonon band structures of nanotubes. Synthesis of nanotubes and other nanomaterials. Experimental determination of nanotube structures and techniques for nanoscale imaging. Theory and measurement of mechanical, thermal, and electronic properties of nanotubes and nanomaterials. Nanofabrication and nanoelectronic devices. Applications of nanotubes.

MECE E6710y Nanofabrication laboratory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): ELEN E6945 or instructor’s permission. Laboratory in techniques for fabrication at the nanometer scale. Electron-beam lithography. Plasma etching and 3D nanofabrication. Thin film deposition. Self-assembly and “bottom up” nanofabrication. Fabrication of and testing of complete nanodevices. A lab fee of $300 is required.

MECE E6720x Nano/microscale thermal transport process

MECE E8020x or E802y Master’s thesis
3–6 pts. Members of the faculty.
Research in an area of mechanical engineering culminating in a verbal presentation and a written thesis document approved by the thesis adviser. Must obtain permission from a thesis adviser to enroll. Recommended enrollment for two terms, one of which can be the summer. A maximum of 6 points of master’s thesis may count toward an M.S. degree, and additional research points cannot be counted. On completion of all master’s thesis credits, the thesis adviser will assign a single grade. Students must use a department-recommended format for thesis writing.

MECE E8100y Advanced topics in fluid mechanics
Prerequisite(s): MECE E6100. May be taken more than once, since its content has minimal overlap between consecutive years. Selected topics from viscous flow, turbulence, compressible flow, rarefied gas dynamics, computational methods, and dynamical systems theory, non-Newtonian fluids, etc.

MECE E8500y Advanced continuum biomechanics
3 pts. Lect: 2. Professor Myers.
Prerequisite(s): Instructor’s permission. The essentials of finite deformation theory of solids and fluids needed to describe mechanical behavior of biological tissue: kinematics of finite deformations, balance laws, principle of material objectivity, theory of constitutive equations, concept of simple solids and simple fluids, approximate constitutive equations, some boundary-value problems. Topics include one- and two-point tensor components with respect to generalized coordinates; finite deformation tensors, such as right and left Cauchy-Green tensors; rate of deformation tensors, such as Rivlin-Ericksen tensors; various forms of objective time derivatives, such as corotational and convected derivatives of tensors; viscous flows of simple fluids; examples of rate and integral type of constitutive equations.

EEME E8600y Advanced topics in control theory
Prerequisite(s): EEME E6601 and E4601 or instructor’s permission. May be taken more than once, since the content changes from year to year, reflecting different topics from control theory such as learning and repetitive control, adaptive control, system identification, Kalman filtering, etc.

MECE E8990x and y Special topics in mechanical engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Instructor’s permission. May be taken for credit more than once. The instructor from the Mechanical Engineering Department and the topics covered will vary from year to year. Intended for students with graduate standing in Mechanical Engineering and other engineering and applied sciences.

MECE E9000x-E9001y and E9002s Graduate research and study
1–3 pts. Members of the faculty.
Theoretical or experimental study or research in graduate areas in mechanical engineering and engineering science.

MECE E9500x and y Graduate seminar
0 pts. Pass/fail only. Professor Schuck.
All doctoral students are required to complete
successfully four semesters of the mechanical engineering seminar MECE E9500.

**MECE E9800x and y Doctoral research instruction**
3, 6, 9, or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in mechanical engineering must register for 12 points of doctoral research instruction. Registration in MECE E9800 may not be used to satisfy the minimum residence requirement for the degree.

**MECE E9900x and y Doctoral dissertation**
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after their coursework has been completed and until the dissertation has been accepted.
Undergraduate Minors
Undergraduate minors are designed to allow engineering and applied science students to study, to a limited extent, a discipline other than their major. Besides engineering minors offered by Columbia Engineering departments, liberal arts minors are also available.

A minor requires at least 15 points of credit, and no more than one course can be taken outside of Columbia or met through AP or IB credit. This includes courses taken through study abroad.

No substitutions or changes of any kind from the approved minors are permitted (see lists below). No appeal for changes will be granted. Please note that the same courses may not be used to satisfy the requirements of more than one minor. No courses taken for pass/fail may be counted for a minor. Minimum GPA for the minor is 2.0. Departments outside the Engineering School have no responsibility for nonengineering minors offered by Engineering.

For a student to receive credit for a course taken while studying abroad, the department offering the minor must approve the course in writing, ahead of the student’s study abroad.

Students must expect a course load that is heavier than usual. In addition, unforeseen course scheduling changes, problems, and conflicts may occur. The School cannot guarantee a satisfactory completion of the minor.

Students interested in establishing a new minor should consult with the Associate Dean of Undergraduate Student Affairs.

**MINOR IN ANTHROPOLOGY**

1. ANTH UN1002: The interpretation of culture (3)  
   or ANTH UN1008: The rise of civilization (3)

Note: UN1002 serves as a preview to sociocultural anthropology, while UN1008 serves as a preview to archaeology.

2–5. Any four courses in the Anthropology department, in ethnomusicology, or taught by an Anthropology instructor, regardless of department. No distribution requirement

**MINOR IN APPLIED MATHEMATICS**

Prospective students should consult the first- and second-year requirements for applied mathematics majors to ensure that prerequisites for the applied mathematics minor are satisfied in the first two years.

Coursework counting toward the applied mathematics minor may not include advanced placement credits.

1. APMA E3101: Linear algebra (3)  
or COMS W3251: Comp. linear algebra (3)  
or MATH UN2010: Linear algebra (3)

2. APMA E3102: Partial differential equations (3)  
or MATH UN3028: Partial differential equations (3)

3–5. Three of the following courses:  
   APMA E4300: Intro to numerical methods (3)  
   APMA E4204: Func of complex variable (3)  
   APMA E4101: Intro to dynamical systems (3)  
   MATH UN2500: Analysis and optimization (3)  
   STAT GU4203: Probability theory (3)  
   STAT GR4204: Statistical inference (3)  
or any other course designated APMA, MATH, STAT, I, EOR, or COMS that is approved by the applied mathematics program adviser.

**MINOR IN APPLIED PHYSICS**

Prospective students should consult the first- and second-year requirements for applied physics majors to ensure that prerequisites for the applied physics minor are satisfied in the first two years.

Coursework counting toward the applied physics minor may not include advanced placement credits.

1. APPH E4901: Problems in applied physics (1)

2. APPH E3200: Mechanics (3)

3. APPH E3100: Intro to quantum mechanics (3)

4. APPH E3300: Applied electromagnetism (3)

5. MSAE E3111: Thermodynamics, kinetic theory, and statistical mechanics (3)

6. Two of the following courses  
   APPH E4010: Intro to nuclear science (3)  
   APPH E4100: Quantum physics of matter (3)  
   APPH E4110: Modern optics (3)  
   APPH E4112: Laser physics (3)  
   APPH E4300: Applied electrodynamics (3)  
   APPH E4301: Intro to plasma physics (3)

**MINOR IN ARCHITECTURE**

1. Studio: One to three of the following courses  
   ARCH UN1020: Intro to architectural design and visual culture (3)
MINOR IN ART HISTORY

1–3. At least one course in three of four of the historical periods: (a) Ancient (up to 400 CE/AD); (b) 400–1400; (c) 1400–1700; (d) 1700–present

4–5. Two additional courses covering two of five world regions: (a) Africa; (b) Asia; (c) Europe; (d) North America; (e) Australia; (f) Latin America; (g) Middle East; (h) medieval Europe

6–7. Two courses from the Department of Art History and Archaeology

MINOR IN BIOMEDICAL ENGINEERING

The Biomedical Engineering program offers a minor that consists of the following six courses. Participation in the minor is subject to the approval of the major program adviser.

1. BIOL UN2005: Introduction to biology, I (3)
2. BIOL UN2006: Introduction to biology, II (3)
3. BMEN E3010: Biomedical engineering, I (3)
4. BMEN E3020: Biomedical engineering, II (3)
5. BMEN E4001: Quantitative physiology, I (3)
6. BMEN E4002: Quantitative physiology, II (3)

MINOR IN CHEMICAL ENGINEERING

Of the six courses required, at least three must have the CHEN, CHEE, or CHAP designator:

1. CHEN E2100: Intro to chemical engineering (3)
2. CHEE E3010: Prin of chemical engineering thermodynamics (3)
   or MSAE E3111: Thermodynamics, kinetic theory, and statistical mechanics (3)
   or MECE E3301: Thermodynamics (3)
   or BMEN E4210: Thermodynamics of biological systems (3)
3. CHEN E3110: Transport phenomena, I (3)
   or EAE E4900: Applied transport and chemical rate phenomena (3)
   or MECE E3100: Intro to mech of fluids (3)
4. CHEN E3161: Fluid mechanics (4)
5. BMEN E3220: Fluid biomechanics (4)
6. CSEE W3827: Fund of computer systems (3)
7. One course from the following: Computational linear algebra: COMS W3251 (4)
   recommended); Linear algebra: MATH UN2101 or APMA E3101 or APMA E2101; Probability statistics: STAT UN4001 or I EOR E4150

MINOR IN CIVIL ENGINEERING

1. CIEN E3121: Structural analysis (3)
   or ENME E3161: Fluid mechanics (4)
   or MECE E3100: Intro to mech of fluids (3)
2. ENME E3105: Mechanics (4)
3. ENME E3113: Mechanics of solids (3)
4. ENME E3125: Structural design (3)
5. CIEN E4241: Geotech eng fundamentals (3)
6. CIEN E3325: Intro to finite elements (3)
7. MECE E3414: Adv strength of materials (3)
8. CIEN E3125: Structural design (3)
9. CIEN E4163: Sustainable water treat/reuse (3)
10. CIEN E3129: Project mgmt for construction (3)
11. CIEN E4131: Prin of construction tech (3)

MINOR IN COMPUTER SCIENCE

Students who pass the Computer Science Advanced Placement Exam A with a 4 or 5 will receive 3 points and exemption from COMS W1004. Taking COMS W1007 is recommended but not required for those students exempt from COMS W1004. Participation in the minor is subject to the approval of the major program adviser. For further information, please see the QuickGuide at https://www.cs.columbia.edu/education/undergraduate/.

Beginning with the class of 2023, the CS core requirements will change as noted below. The following are required courses toward the CS Core for the class of 2023 and beyond:

1. COMS W1004: Intro to computer science and programming in Java (3)
2. COMS W1007: Honors intro to comp sci (3)
3. COMS W3134: Data structures in Java (3)
4. COMS W3137: Honors data structures and algorithms (4)
5. COMS W3157: Advanced programming (4)
6. COMS W3203: Discrete mathematics (4)
7. COMS W3261: Comp science theory (3)
8. CSEE W3827: Fund of computer systems (3)
9. or a 4000-level COMS technical elective

MINOR IN DANCE

The dance minor consists of five 3-point courses. Please note that no performance/choreography courses below count toward the nontech requirement for Engineering students.

1–2. History/criticism: Two of the following:
   DNCE BC2565: World dance history (3)
   DNCE BC2570: Dance in New York City (3)
   DNCE BC3000: From the page to the dance stage (3)
   DNCE BC3001: Western theatrical dance from the Renaissance to the 1960s (3)
   DNCE BC3002: Choreographing race (3)
   DNCE BC3200: Dance in film (3)
   DNCE BC3240: Seeing the body (3)
   DNCE BC3550: Dance in Africa (3)
   DNCE BC3567: Dance of India (3)
   DNCE BC3576: Dance criticism (3)
   DNCE BC3577: Performing the political (3)

3–4. Performance/choreography: Two of the following:
   DNCE BC2563: Dance composition: form (3)
   DNCE BC2564: Dance composition: content (3)
   DNCE BC2567: Music for dance (3)
   DNCE BC3601-3607: Rehearsal and performance in dance (1–3)

5. One elective

MINOR IN EARTH AND ENVIRONMENTAL ENGINEERING

1–3. Three of the following courses:
   EAEE E3103: Energy, minerals, and mat syst (3)
   CIEE E3255: Environmental control and pollution reduction systems (3)
   EAEE E4001: Industrial ecology of earth res (3)
   EAEE E4003: Intro to aquatic chemistry (3)
   EAEE E4004: Physical processing and recovery of solids (3)
   EAEE E4006: Field methods for environ eng (3)
   EAEE E4009: GIS for resource, environment, and infrastructure management (3)
   EAEE E4150: Air pollution prevention and control (3)
   EAEE E4160: Solids and hazardous waste management (3)
   EAEE E4200: Introduction to sustainable production of earth mineral & metal resources (3)
   EAEE E4257: Environ data analysis and modeling (3)
   EAEE E4361: Econ of earth res industries (3)
   EACH E4560: Particle technology (3)
4–6. Three of the following courses:
- CHEE E3010: Prin of chemical engineering thermodynamics (3)
- CHEE E3110: Transport phenomena, I (3)
- CIEN E3141: Soil mechanics (3)
- CIEE E3250: Hydrosystems engineering (3)
- ECIA W4100: Mgmt and dev of water systems (3)
- CIEE E4163: Environ eng: wastewater (3)
- EAEE E4190: Photovoltaic systems eng (3)
- MECE E4211: Energy: sources and conv (3)
- CIEN E4250: Waste contain design and prac (3)
- CHEE E4252: Intro to surface and colloid chem (3)
- CIEE E4252: Environmental engineering (3)
- CIEE E4257: Groundwater contaminant transport and remediation (3)
- CHEN E4410: Environmental control technology (3)

MINOR IN EAST ASIAN STUDIES

1–5. Any two of the survey courses on Chinese, Japanese, Korean, Tibetan, or Vietnamese civilization (ASCE UN1359, UN1361, UN1363, UN1365, UN1367), plus three elective courses dealing with East Asia

Note: The elective courses may be taken in departments outside of East Asian Languages and Cultures. The minor does not include a language requirement. However, one semester of an East Asian language class may be used to fulfill one of the three electives, as long as at least two semesters of that language have been taken. Placement exams may not be used in place of these courses.

MINOR IN ECONOMICS

1. ECON UN1105: Principles of economics (4)
2. ECON UN3211: Intermediate microeconomics (4)
3. ECON UN3213: Intermediate macroeconomics (4)
4. ECON UN3412: Introduction to econometrics (4)

Note: UN1105 is a prerequisite for UN3211, UN3213, and UN3412. Students must have completed Calculus I before taking UN3213, Calculus II before taking UN3211, and one of the introductory statistics courses (see list) before taking UN3412.

5–6. Electives: Two of the following courses:
- ECON UN2010: American economy (3)
- ECON UN2257: Global economy (3)
- ECON UN3025: Financial economics (3)
- ECON UN3265: Econ of money and banking (3)
- ECON UN3901: Economics of education (3)

- ECON UN3952: Macro and formation of expectations (3)
- ECON GU4020: Econ of uncertainty and info (3)
- ECON GU4211: Advanced microeconomics (3)
- ECON GU4213: Advanced macroeconomics (3)
- ECON GU4230: Economics of NYC (3)
- ECON GU4251: Industrial organization (3)
- ECON GU4260: Market design (3)
- ECON GU4280: Corporate finance (3)
- ECON GU4301: Economic growth and development (3)
- ECON GU4321: Economic development (3)
- ECON GU4370: Political economy (3)
- ECON GU4400: Labor economics (3)
- ECON GU4412: Advanced econometrics (3)
- ECON GU4413: Economics of time series and forecasting (3)
- ECON GU4415: Game theory (3)
- ECON GU4438: Economics of race in the U.S. (3)
- ECON GU4465: Public economics (3)
- ECON GU4480: Gender and applied economics (3)
- ECON GU5000: International trade (3)
- ECON GU5450: International macro (3)
- ECON GU7000: Financial crises (3)
- ECON GU7100: Finance and the real economy (3)
- ECON GU7500: Globalization and its risks (3)
- ECON GU8480: Behavioral economics (3)
- ECON GU8550: Cognitive mechanisms and economic behavior (4)
- ECON GU8680: Behavioral finance (3)

Note: Electives may be taken only after the completion of both UN3211 and UN3213, with the exception of UN2257 and UN2105, which may be taken after completion of UN1105. Some of the elective courses listed above have additional prerequisites. Courses may be taken only after the completion of all prerequisites. Please see the Columbia College bulletin for course descriptions and complete lists of prerequisites.

7. Statistics: One of the following three probability and statistics options (course or sequence):
   a. SIEO W3600 (or STAT GU4001): Intro to probability and statistics (3)
   b. IEOR E3658: Probability and E4307: Applied statistical models (3)
   c. STAT UN4203 (or GR5203): Intro to probability and statistics and STAT UN4204 (or GR5204): Statistical inference (3)

Notes:
- The statistics course must be finished before taking UN3412, and it is recommended that students take UN3412 in the semester following the statistics course.
- Some courses done as part of the economics minor may count toward satisfying the School's nontechnical requirements. However, other courses, such as UN3412: Intro to econometrics, may not be applied toward satisfaction of the nontechnical course requirements. To determine which economics class can count toward the nontechnical elective requirement, please consult the nontechnical elective section of this bulletin for further details.
- Students with AP credit for economics and an exemption for UN1105 may use the credit toward the minor.
- Transfer or study abroad credits may not be applied to fulfill the requirements of the economics minor.

MINOR IN ELECTRICAL ENGINEERING

1. ELEN E1201: Intro to electrical eng (3.5) (May be replaced by a similar course or roughly equivalent experience)
2. ELEN E3201: Circuit analysis (3.5)
3. CSEE W3827: Fund of computer systems (3)
4. ELEN E3081 and ELEN E3082: Electrical engineering labs (2)
5. ELEN E3801: Signals and systems (3.5)
6. ELEN E3106: Solid-state dev and mat (3.5) or ELEN E3401: Electromagnetics (4)

Note: Not available to computer engineering majors

MINOR IN ENGINEERING MECHANICS

1. ENME E3105: Mechanics (4)
2. ENME E3113: Mechanics of solids (3)
3. ENME E3161: Fluid mechanics (4) or MECE E3100: Intro to mech of fluids (3)

4–6. Electives: Three of the following:
   - ENME E3106: Dynamics and vibrations (3)
   - ENME E3114: Exp mechanics of materials (4) or MECE E3414: Adv strength of materials (3)
   - CIEN E3121: Structural analysis (3)
   - ENME E4202: Advanced mechanics (3)
   - ENME E4113: Advanced mechanics of solids (3)
   - ENME E4114: Mech of fracture and fatigue (3)
   - ENME E4214: Theory of plates and shells (3)
   - ENME E4215: Theory of vibrations (3)
   - MECE E3301: Thermodynamics (3)

MINOR IN ENGLISH AND COMPARATIVE LITERATURE

1–5. Any five courses in the English Department with no distribution requirement. No speech courses, only one writing course and excluding ENGL CC1010, may be taken; total 15 points.
MINOR IN ENTREPRENEURSHIP AND INNOVATION
Minimum: 15 points
1–2. Required courses:
   IEOE 2261: Accounting and finance (3)
   and IEOE 4998: Managing technological innovation and entrepreneurship (3)
3–5. Electives: Three of the following courses:
   BIOT GU4180: Entrepreneurship in biotech (3)
   BUSI W3021: Marketing management (3)
   CHEN E4020: Protection of industrial and intellectual property (3)
   CIEG E4136: Global entrepreneurship in civil engineering (3)
   COMS W4444: Program and problem solving (3)
   COMS W4460: Principles of innovation in biotechnology (3)
   ECON GU4280: Corporate finance (3)
   IEOE 4403: Corporate finance for engineers (3)
   IEOE 4510: Project management (3)
   IEOE 4500: Entrepreneurial business creation for engineers (3)
   IEOE 4560: Lean launchpad (3)
(by application only with adviser approval)

MINOR IN ETHNICITY AND RACE
1. The following course:
   CSER UN1010: Introduction to comparative ethnic studies (3)
2. One of the following courses:
   CSER UN3928: Colonization/decolonization (3)
   CSER UN3942: Race and racisms (3)
3–5. Three additional CSER Courses with approval from the Department

MINOR IN FILM AND MEDIA STUDIES
1. FILM UN1000: Introduction to film and media studies (3)
2. History courses: one of the following:
   FILM UN2010: Cinema history 1: Beginning—1930 (3)
   FILM UN2020: Cinema History 2: 1930–60 (3)
   FILM UN2030: Cinema History 3: 1960–90 (3)
   FILM UN2040: Cinema History 4: after 1990 (3)
3–5. Any three courses offered by the Department of Film and Media Studies excluding laboratory courses

MINOR IN FRENCH AND FRANCOPHONE STUDIES
15 points beyond second-year French
1–2. FREN UN3409 and UN3410: Intro to French and francophone history and Intro to French and francophone literature (3, 3)
3–5. Three additional courses in French beyond satisfaction of the language requirement

MINOR IN GERMAN
15 points beyond second-year German
1. GERM UN3001 or 3002: Adv German, I or II (3)
2. GERM UN3333: Intro to German literature (3)
3. One of the period survey courses in German literature and culture, GERM UN3442, UN3443, UN3444, UN3445
4–5. Two courses taken from any 3000/4000-level German or CompLit-German courses taught in German or English

MINOR IN GREEK OR LATIN
1–4. A minimum of 13 points in the chosen language at the 1200 level or higher
5. 3 points in ancient history of the appropriate civilization

MINOR IN HISPANIC STUDIES
1. SPAN UN3300: Adv language through content (3)
2–3. SPAN UN3349 and UN3350: Spanish cultures, I and II (3, 3)
4–5. One additional 3000-level elective course in the Department of Latin American and Iberian Cultures
(Note: Please see the director of undergraduate studies in the Department of Latin American and Iberian Cultures for more information and to declare the minor.)

MINOR IN IN HISTORY
1–5. Minimum 5 courses in the History Department with no distribution or seminar requirements. Transfer or study-abroad credits may not be applied.

MINOR IN INDUSTRIAL ENGINEERING
1. IEOE E3658: Probability for engineers (4)
   or STAT GU4001: Intro to probability and statistics (3)
2. IEOE E3608: Foundations of optimization (3)
3. IEOE E3402: Production inventory planning and control (4)
4. IEOE E4003: Corporate finance for engineers (3)
5–6. Electives: Two IEOE courses of interest and approved by a faculty adviser¹

¹Electives should be 3000-level or higher.

MINOR IN INNOVATION
1–3. Three of the following courses:
   AMST UN3931: Topics in American Studies
   (languages of America/language contact) (3)
   ENGL GU4901: History of the English language (3)
   LING UN3101: Introduction to linguistics (3)
   LING UN3102: Endangered languages in the global city (3)
   LING UN3103: Language, brain, and mind (3)
   LING GU4108: Language history (3)
   LING GU4120: Language documentation and field methods (3)
   LING GU4171: Languages of Africa (3)
   LING GU4190: Discourse and pragmatics (3)
   LING GU4376: Phonetics and phonology (3)
   LING GU4800: Language and society (3)
   LING GU4903: Syntax (3)
4–6. Three additional courses from either a) the core linguistics courses, or b) a linguistics-related course from another department subject to approval from the program. Courses previously approved include those listed below:

Anthropology:
   ANTH UN1009: Introduction to language and culture (3)
   ANTH GU4042: Agent, person, subject, self (3)
   ANTH GR6067: Language and its limits (3)
   ANTH GR6125: Language, culture, and power (3)

Chinese:
   CHNS GU4019: History of Chinese language (3)

Computer Science:
   COMS W4705: Natural language processing (3)
   COMS W4995: Topics in computer science (with approval) (3)
   COMS E6998: Topics in computer science (with approval) (3)

Comparative language and society:
   CLPS GU4111: World philology (3)

French:
   FREN BC3011: History of the French language (3)

Hungarian:
   HUNG UN3343: Descriptive grammar of Hungarian (3)

Philosophy:
   PHIL UN2685: Introduction to philosophy of language (3)
   PHIL UN3411: Symbolic logic (3)
   PHIL UN3685: Philosophy of language (3)
   PHIL GU4490: Language and mind (3)

Psychology:
   PSYC UN2215: Cognition and the brain (3)
   PSYC UN2440: Language and the brain (3)
   PSYC UN2450: Behavioral neuroscience (3)
4. Four of the following courses:

- MECE E3100: Intro to mechanics of fluids (3)
- ENME E3161: Fluid mechanics (4)
- or CHEN E3110: Transport phenomena, I (3)
- or EAAE E3200: App transport and chemical rate phenomena (3)
- ENME E3105: Mechanics (4)
- ENME E3106: Dynamics and vibrations (3)
- MECE E3301: Thermodynamics (3)
- or CHEE E3010: Principles of chemical engineering thermodynamics (3)
- or MSAE E3111: Thermodynamics, kinetic theory, and statistical mechanics (3)
- ENME E3113: Mechanics of solids (3)
- MECE E3408: Comp graphics and design (3)
- MECE E3311: Heat transfer (3)
- MECE E3610: Materials and processes in manufacturing (3)
- EEME E3601: Classical control systems (3)

5–6. Electives: Two additional mechanical engineering courses from either the above list or the following (not all courses in this list are given every year):

- MECE E3401: Mechanics of machines (3)
- MECE E3450: Computer-aided design (3)

Any 3-credit 4000-level courses listed in the Mechanical Engineering Bulletin can also be used to fulfill these additional course requirements.

MINOR IN MIDDLE EASTERN, SOUTH ASIAN, AND AFRICAN STUDIES

1–5. Five courses, to be chosen with the approval of the MESAAS Director of Undergraduate Studies; no elementary or intermediate language courses may be counted.

MINOR IN MUSIC

1. MUSI UN2318-2319: Music theory, I and II (3, 3)
2. MUSI UN1312-1313: Intro ear training (1)
3. MUSI UN2314: Ear training, I (1)
4. One of the following courses:
   - MUSI UN3128: History of Western music, I (3)
   - MUSI UN3129: History of Western music, II (3)
5–6. Any two electives at the 3000 or 4000 level. See also the Engineering-approved nontechnical electives in music (page 10)

Notes:
- Students must successfully place out of MUSI UN1002: Fundamentals of music (3.0 points).
- Steps 4 and 5 must be completed to fulfill the nontechnical elective requirement for graduation.
- Students are strongly encouraged to take HUMA UN1123: Masterpieces of Western music (3.0 points) from the list of nontechnical electives.

MINOR IN OPERATIONS RESEARCH

1. IEOR E3658: Probability for engineers or STAT GU4001: Intro to probability and statistics (4)
2. IEOR E3106: Stochastic systems and applications (3)
3. IEOR E3608: Foundations of optimization (4)
4. IEOR E3404: Simulation modeling and analysis (4)
5–6. Electives: Two IEOR courses (6 pts) of interest and approved by a faculty adviser.¹ IEOR E3402: Production-inventory planning and control (3) is strongly recommended

Note: In addition to the required courses, students majoring in industrial engineering must take three operations research courses that are not used to satisfy the requirements of their major.

¹ Electives should be 3000-level or higher.

MINOR IN PHILOSOPHY

1–5. Any five courses in the Philosophy Department with no distribution requirement; total 15 points. See also the list of exceptions under Elective Nontechnical Courses.

Note: Please be aware that some philosophy courses may not count as nontechnical electives.

MINOR IN POLITICAL SCIENCE

1–2. Two of the following courses:
- POLS UN1101: Intro to political theory (3)
- POLS UN1201: Intro to American govt and politics (3)
- POLS UN1501: Intro to comparative politics (3)
- POLS UN1601: International politics (3)
3–5. Any three courses in the Political Science Department with no distribution requirement; total 9 points

MINOR IN PSYCHOLOGY

1. PSYC UN1001: The science of psychology (3)
2–5. Any four courses from, at a minimum, two of the three groups below:

I. PERCEPTION AND COGNITION

Courses numbered in the 2200s, 3200s, or 4200s

II. PSYCHOBIOLOGY AND NEUROSCIENCE

PSYC UN2430: Cognitive neuroscience (3)
Courses numbered in the 2400s, 3400s, or 4400s

III. SOCIAL, PERSONALITY, AND ABNORMAL

Courses numbered in the 2600s, 3600s, or 4600s

MINOR IN RELIGION

1–5. Five courses (total 15 points), one of which must be at the 2000 level

MINOR IN SOCIOLOGY

1. SOCI UN1000: The social world (3)
2. SOCI UN3000: Social theory (3)
3–5. Any two 2000-, 3000-, or 4000-level courses offered by the Department of Sociology; total 6 points

MINOR IN STATISTICS

1. STAT UN1101: Intro to statistics (w/o calculus) (3)
2. STAT UN2102: App statistical computing (3)
3. STAT UN2103: App linear regression analysis (3)
MINOR IN SUSTAINABLE ENGINEERING

Total of six courses from the following lists required with no substitutions allowed:

1–4. Four of the following courses:
   - EAE E2002: Alternative energy sources (3)
   - EAE E2100: Better planet by design (3)
   - CIEE E3250: Hydrosystems engineering (3)
   - CIEE E3260: Eng for comm dev (3)
   - EAE E3901: Environmental microbiology (3)
   - EAE E4001: Industrial ecology (3)
   - ECIA W4100: Mgmt and dev of water systems (3)
   - APPH E4130: Physics of solar energy (3)
   - EAE E4190: Photovoltaic systems eng and sustainability (3)
   - MECE E4211: Energy sources and conversion (3)
   - MECE E4312: Solar thermal engineering (3)
   - EAE E4257: Environmental data analysis (3)
   - MECE E4314: Dynamics of green buildings (3)
   - EESC GU4404: Regional climate and climate impacts (3)

5. One of the following courses:
   - ECON UN2257: Global economy (3)

Note: If courses in Group 5 or 6 are not available, requesting approval for a similar course from the groups “Economics” or “Law, Policy and Human Rights,” respectively from the Columbia College Sustainable Development course list is possible (bulletin.columbia.edu/columbia-college/departments-instruction/sustainable-development/#coursestext).
Interdisciplinary Courses and Professional Development and Leadership Program
Of the following courses, some may be requirements for degree programs, and others may be taken as electives. See your departmental program of study or consult with an adviser for more information.

**ENGI E1102x and y The art of engineering**
Core requirement for all entering SEAS students. A bridge between the science-oriented, high school way of thinking and the engineering point of view. Fundamental concepts of math and science are reviewed and reframed in an engineering context, with numerous examples of each concept drawn from all disciplines of engineering represented at Columbia. Nontechnical issues of importance in professional engineering practice such as ethics, engineering project management, and societal impact are addressed. Lab fee: $350.

**ENGI E4200x Global Engineering**
3 pts. Lect 3. Professor Bourtsalas.
Prerequisite(s): Students must be enrolled in the Global Engineering Track (GET) elective specialization. Introduces students to contemporary cases in engineering that impact the world globally and locally. Taught by Columbia Engineering faculty members, approaching cases in an interdisciplinary manner, brings students together from across the MS programs. Focuses on the School’s vision of Engineering for Humanity in five areas: Sustainability, Health, Security, Connectedness, and Creativity.

**ENGI E4201s Global engineering fieldwork**
Prerequisite(s): Students must be enrolled in the Global Engineering Track (GET) elective specialization. Instructor's written approval. Final reports required. May not be audited. International students must consult with the International Students and Scholars Office.

**ENGI E4300x Design justice: human-centered design and social justice**
3 pts. Professors Chilton, Patton, and West.
Prerequisite(s): IEME E4200 or COMS W4170 or instructor's permission. Introduction to Human-Centered Design and Innovation. Unpack the role of design in the market economy for an individual consumer, for a designer/developer, and for an enterprise or other organization. Consider how designing in good faith for most can lead to injustice for some. Examine how to use the PROP framework of the Columbia School of Social Work—power, race, oppression, and privilege can be executed through the design process. Equip students with tools to engage in the design process and to facilitate the engagement of others. Explore strategies for guiding design and innovation toward more just solutions.

**ENGI E4990x and y Advanced master’s research**
1–6 pts.
Advanced master's research for students within departments that offer master's research specialization. Students may enroll for 1–6 credits per semester, for a maximum of 12 credits required for the master's program. Note: open to students in master's research only.

**ENGI E8000x, y, and s Doctoral fieldwork**
1 pts.
Fieldwork is integral to the academic preparation and professional development of doctoral students. This course provides the academic framework for fieldwork experience required for the student’s program of study. Fieldwork documentation and faculty adviser approval is required prior to registration. A final written report must be submitted. This course will count toward the degree program and cannot be taken for pass/fail credit or audited. With approval from the department chair or the doctoral program director, doctoral students can register for this course at most twice. In rare situations, exceptions may be granted by the Dean's Office to register for the course more than twice (e.g., doctoral students funded by industrial grants who wish to perform doctoral fieldwork for their corporate sponsor). The doctoral student must be registered for this course during the same term as the fieldwork experience.

For information on courses in other divisions of the University, please consult the bulletins of Columbia College and the Graduate School of Arts and Sciences.
The Professional Development and Leadership (PDL) program educates students to maximize performance and achieve their full potential to become engineering leaders. Core sessions focus on development of skills and perspectives needed to compete and succeed in a fast-changing technical climate. Topics include professional portfolio (resume, cover letter, business writing, social media presence), communication skills, leadership, ethics, life management (stress, sleep, and time management) and more. Elective sessions include effective presentations, emotional intelligence, data visualization, and interview preparation.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements. Undergraduate students are encouraged to participate in the professional development and leadership program.

PROFESSIONAL DEVELOPMENT AND LEADERSHIP STAFF
Gabriella Lilienthal, Assistant Director
Kaitlynn Liriano, PDL Officer
Jenny Mok, Senior Associate Dean
Elizabeth Strauss, Assistant Dean
pdl-seas@columbia.edu
pdl.engineering.columbia.edu

PROFESSIONAL DEVELOPMENT AND LEADERSHIP CORE FACULTY
Chuck Garcia: Communication
Hélio Fred Garcia: Ethics and Integrity
Sophia Hyoseon Lee: English Communication
Gabriella Lilienthal: Social Media
Jenny Mok: Resume
Elizabeth Strauss: Business Writing

PROFESSIONAL DEVELOPMENT AND LEADERSHIP COURSES

M.S. Course
ENGI E4000x and y Professional development and leadership for engineers and applied scientists
0 pts. The PDL Instructional Team.
The PDL course aims to enhance and expand Columbia Engineering graduate students’ interpersonal, professional, and leadership skills, through five core sessions, covering (1) in-person communication skills; (2) resume; (3) business writing; (4) social media and the job search; and (5) academic and professional ethics and integrity. ENGI E4000 also requires 5 elective sessions to further students’ development based on their personal interests. Students must select at least one life management elective and one interview elective. This course is offered at the Pass/D/Fail grading option.

Doctoral Courses
ENGI E6001x and y Professional development and leadership for first year doctoral students
0 pts. The PDL Instructional Team.
For first year doctoral students, emphasizing the skills needed for success in orienting them to Columbia and doctoral studies, including teaching and presentation skills (i.e., Microteaching, how to grade, hold office hours, conduct recitations, etc.); cultivating relationships with mentors, faculty, and colleagues; inclusivity; managing your budget; wellness; research and academic integrity and ethics.

ENGI E6002x and y Professional development and leadership for second year doctoral students
0 pts. The PDL Instructional Team.
For second year doctoral students, emphasizing the skills needed for continued success in the doctoral program, including presentation and communication skills; academic writing skills; academic conference preparation; resiliency and project management skills.

ENGI E6003x and y Professional development and leadership for third year doctoral students
0 pts. The PDL Instructional Team.
For third year doctoral students to facilitate career exploration including teaching, presentation and communication skills; public speaking and facilitation; CV and resume writing; and Getting Things Done.

ENGI E6004x and y Professional development and leadership for doctoral students: fourth year
0 pts. The PDL Instructional Team.
For fourth year doctoral students to facilitate career exploration including teaching, presentation and communication skills; public speaking and facilitation; CV and resume writing; and Getting Things Done.
GRADUATE CAREER PLACEMENT

Austin Cartagena, Career Placement & PDL Officer
Ryan Day, Manager
Jenny Mak, Senior Associate Dean
Elizabeth Strauss, Assistant Dean
seas-gcp@columbia.edu
careers.engineering.columbia.edu

While enrolled in a graduate program at Columbia Engineering you will also be coached by your dedicated Career Placement Officer. We look forward to working with you on your professional development and job search throughout your time at Columbia.

Austin Cartagena
Computer Science; Mechanical Engineering

Michal Dar
Industrial Engineering and Operations Research (BA)

David Fitzgerald
Industrial Engineering and Operations Research (OR)

Kristen Henlin
Applied Physics, Applied Mathematics, Medical Physics, Material Science and Engineering; Biomedical Engineering

John Hyde
Data Science

Jennifer Lee
Electrical Engineering, Computer Engineering

Mindi Levinson
Industrial Engineering and Operations Research (MSE & IE)

Emily McCormack
Civil Engineering and Engineering Mechanics; Mechanical Engineering

Raina Ranaghan
Chemical Engineering; Earth and Environmental Engineering

Sara Yllescas
Computer Science

ENGLISH COMMUNICATION COURSES

M.S. Courses

ENGI E5000x, y, and s Workplace communication in English
ENGI E5001x, y, and s Professional presentation
ENGI E5002x, y, and s Professional communication in English
ENGI E5003x, y, and s Academic writing
ENGI E5009x, y, and s English communication independent studies

0 pts. Lect: 1.7. Professor Lee.
English communication proficiency is important for academic achievement and career success. In small group settings, interactions with instructor and fellow students to improve communication and writing skills. Individual tutoring sessions offered. Note: open only to Columbia Engineering master's students. Grading is Pass/D/Fail.

Ph.D. Courses

ENGI E7000x, y, and s English communication
ENGI E7001x, y, and s Professional presentation
ENGI E7002x, y, and s Advanced academic writing
ENGI E7009x, y, and s English communication independent studies

0 pts. Lect: 1.7. Professor Lee.
English communication proficiency is important for academic achievement and career success. In small group settings, interactions with instructor and fellow students to improve communication and writing skills. Individual tutoring sessions offered. Note: open only to Columbia Engineering Ph.D. and M.S. to Ph.D.-track students. Grading is Pass/D/Fail.
University and School Policies, Procedures, and Regulations
REGISTRATION AND ENROLLMENT

Registration is the process that reserves seats in particular classes for eligible students. It is accomplished by following the procedures announced in advance of each term’s registration period.

Enrollment is the completion of the registration process and affords the full rights and privileges of student status. Enrollment is accomplished by the payment or other satisfaction of tuition and fees and by the satisfaction of other obligations to the University.

Registration alone does not guarantee enrollment nor does registration alone guarantee the right to participate in class. In some cases, students will need to obtain the approval of the instructor, or of a representative of the department that offers a course, or permission of the School offering the class. Students should check this bulletin, their registration instructions, the Directory of Classes, and also with an adviser for all approvals that may be required.

To comply with current and anticipated Internal Revenue Service mandates, the University requires all students who will be receiving financial aid or payment through the University payroll system to report their Social Security number at the time of admission. Newly admitted students who do not have a Social Security number should obtain one well in advance of their first registration. International students should consult the International Students and Scholars Office, located at 524 Riverside Drive (212-854-3587), for further information.

Special billing authorization is required of all students whose bills are to be sent to a third party for payment. Students who are not citizens of the United States and who need authorization for special billing of tuition and/or fees to foreign institutions, agencies, or sponsors should go to the International Students and Scholars Office with two copies of the sponsorship letter.

University Regulations

Each person whose enrollment has been completed is considered a student of the University during the term for which they are enrolled unless their connection with the University is officially severed by being withdrawn or for other reasons. No student enrolled in any school or college of the University shall at the same time be enrolled in any other school or college, either of Columbia University or of any other institution, without the specific authorization of the dean or director of the school or college of the University in which they are first enrolled.

The privileges of the University are not available to any student until enrollment has been completed. Students are not permitted to attend any University course for which they are not officially enrolled or for which they have not officially filed a program unless they have been granted auditing privileges.

The University reserves the right to withhold the privileges of registration and enrollment or any other University privilege from any person who has administrative obligations to the University.

Continuous registration until completion of all requirements is obligatory for each degree. Students are exempted from the requirement to register continuously only when granted a leave of absence by the Committee on Academic Standing (for undergraduate students) or the Office of Graduate Student Affairs (for graduate students).

Registration Instructions

Registration instructions are announced in advance of each registration period by the Registrar. Students should consult these instructions for the exact dates and times of registration activities. Students must be sure to obtain all necessary written course approvals and advisers’ signatures before registering. Undergraduate students who have not registered for a full-time course load by the end of the change of program period will be withdrawn, as will graduate students who have not registered for any coursework by the end of the change of program period. International students enrolled in graduate degree programs must maintain full-time status until degree completion.

DEGREE REQUIREMENTS AND SATISFACTORY PROGRESS

Undergraduate

Undergraduate students are required to complete the School’s degree requirements and graduate in eight academic terms. Full-time
undergraduate registration is defined as at least 12 credits per term. However, in order to complete the degree, students must be averaging 16 credits per term. Students may not register for point loads greater than 21 points per term without approval from the Committee on Academic Standing.

To be eligible to receive the Bachelor of Science degree, a student must complete the courses prescribed in a faculty-approved major/program (or faculty-authorized substitutions) and achieve a minimum cumulative grade-point average (GPA) of 2.0. Although the minimum number of academic credits is 128 for the B.S. degree, some programs of the School require a greater number of credits in order to complete all the requirements. Undergraduate engineering degrees are awarded only to students who have completed at least 60 points of coursework at Columbia. No credit is earned for duplicate courses or for courses that are taken pass/fail and the final grade is a P, with the exception of two nontechnical electives at the 3000 level or above and physical education courses, as noted below.

Undergraduates in the programs accredited by the Engineering Accreditation Commission of ABET (Biomedical Engineering, Chemical Engineering, Civil Engineering, Earth and Environmental Engineering, Electrical Engineering, and Mechanical Engineering) satisfy ABET requirements by taking the courses in prescribed programs, which have been designed by the departments so as to meet the ABET criteria.

**Attendance**

Students are expected to attend their classes and laboratory periods. Instructors may consider attendance in assessing a student’s performance and may require a certain level of attendance for passing a course.

**Graduate**

Graduate students are required to complete the School’s degree requirements as outlined on page 22 (The Graduate Programs). Full-time graduate registration is defined as at least 12 credits per term. A typical course load is 12–15 credits per term, not including the last term.

A graduate student who has matriculated in an M.S. program or is a nondegree student is considered to be making normal progress if they have earned a cumulative GPA of 2.5 or minimum GPA required by the academic department, whichever is higher. Candidates in the Doctor of Engineering Science (Eng.Sc.D.) program are expected to achieve a 3.0 GPA or minimum GPA required by the academic department, whichever is higher.

Graduate students (on-campus and online students) who do not meet the minimum cumulative GPA of the school and the department will be placed on academic probation. During the probation period students must meet with their department to discuss and develop an academic plan to improve their overall GPA. If the student does not meet the academic benchmarks required by their department after the term in which they have been placed on probation, then they may be asked to leave the School permanently. Degree requirements for master’s degrees must be completed within five years; those for the doctoral degrees must be completed within seven years. A minimum cumulative GPA of 2.5 (in all courses taken as a degree candidate) is required for the M.S. degree; a minimum GPA of 3.0 or minimum GPA required by the academic department, whichever is higher, is required for the Doctor of Engineering Science (Eng.Sc.D.) and the Doctor of Philosophy degrees. The minimum residence requirement for each Columbia graduate degree is 30 points of coursework completed at Columbia.

**Changes in Registration**

An undergraduate student who wishes to drop or add courses or to make other changes in their program of study after the change of program period must obtain the approval of their CSA adviser. A student who wishes to drop or add a course in their major must also obtain department approval. The deadline for making program changes in each term is shown in the Academic Calendar. Note: the drop-date for Columbia Core courses is the second week of the semester. After these dates, undergraduate students must petition the Committee on Academic Standing; graduate students must petition the Office of Graduate Student Affairs. For courses dropped after these dates, no adjustment of fees will be made. Failure to attend a class will be indicated by a permanent unofficial withdrawal (UW) on the transcript.

**Transfer Credits**

Undergraduate students may obtain academic credit toward the B.S. degree by completing coursework at other accredited four-year institutions. Normally, this credit is earned during the summer. To count as credit toward the degree, a course taken elsewhere must have an equivalent at Columbia University and the student must achieve a grade of at least B. An exception to this policy is made for students enrolled in an approved study abroad program. Students in an approved study abroad program will receive transfer credit if they earn a grade of C or higher. To transfer credit, a student must obtain prior approval from their CSA adviser and the department before taking such courses. A course description and syllabus should be furnished as a part of the approval process. Courses taken before the receipt of the high school diploma may not be credited toward the B.S. degree. A maximum of 6 credits may be applied toward the degree for college courses taken following the receipt of a high school diploma and initial enrollment at Columbia University. Master’s degree students are not eligible for transfer credits.

Students possessing a conferred M.S. degree upon entry into a Ph.D. program may be awarded 2 residence units toward their Ph.D., as well as 30 points of advanced standing toward their Ph.D. or Eng.Sc.D. with departmental approval.

**Examinations**

**Midterm examinations:** Instructors generally schedule these in late October and mid-March.

**Final examinations:** These are given at the end of each term. The Master University Examination Schedule is available online and is confirmed by November 1 for the fall term and April 1 for the spring term. This schedule is
sent to all academic departments and is available for viewing on the Columbia website. Students should consult with their instructors for any changes to the exam schedule. Examinations will not be rescheduled to accommodate travel plans.

Note: If a student has three final examinations scheduled during one calendar day, as certified by the Registrar, an arrangement may be made with one of the student’s instructors to take that examination at another, mutually convenient time during the final examination period. This refers to a calendar day, not a 24-hour time period. Undergraduate students unable to make suitable arrangements on their own should contact their CSA adviser. Graduate students should contact the Office of Graduate Student Affairs.

Transcripts and Certifications
For information on the Federal Family Education Rights and Privacy Act (FERPA) of 1974, please visit facets.columbia.edu—Essential Policies for the Columbia Community. Information on obtaining University transcripts and certifications will be found as a subhead under Essential Resources.

Report of Grades
Grades can be viewed by using the Student Services Online feature located on the Student Services home page at columbia.edu/students. If you need an official printed report, you must request a transcript (please see Transcripts and Certifications above).

All graduate students must have a current mailing address on file with the Registrar’s Office.

Transcript Notations
The grading system is as follows: A, excellent; B, good; C, satisfactory; D, poor but passing; F, failure (a final grade not subject to re-examination). Occasionally, P (Pass) is the only passing option available. The grade-point average is computed on the basis of the following index: A=4, B=3, C=2, D=1, F=0. Designations of + or – (used only with A, B, C) are equivalent to 0.33 (i.e., B+=3.33; B=2.67). Grades of P, INC, UW, and MU will not be included in the computation of the grade-point average.

R (registration credit; no qualitative grade earned): not accepted for degree credit in any program. R credit is not available to undergraduate students for academic classes. In some divisions of the University, the instructor may stipulate conditions for the grade and report a failure if those conditions are not satisfied. The R notation will be given only to those students who indicate, upon registration and to the instructor, their intention to take the course for R, or who, with the approval of the instructor, file written notice of change of intention with the registrar not later than the last day for change of program. Students wishing to change to R credit after this date are required to submit written approval from the Office of Graduate Student Affairs and the course instructor to the registrar. The request to change to R credit must be made by the last day to change a course grading option. A course that has been taken for R credit may not be repeated later for examination credit and cannot be uncovered under any circumstances. The mark of R does not count toward degree requirements for graduate students. The mark of R is automatically given in Doctoral Research Instruction courses.

UW (unofficial withdrawal): given to students who discontinue attendance in a course but are still officially registered for it, or who fail to take a final examination without an authorized excuse.

IN (incomplete): granted only in the case of incapacitating illness as certified by the Health Services at Columbia, serious family emergency, or circumstances of comparable gravity. Undergraduate students request an IN by filling out the Incomplete Request Form with their CSA adviser prior to the final exam for the course in the semester of enrollment. Students requesting an IN must gain permission from both the Committee on Academic Standing (CAS) and the instructor. Graduate students should contact their instructor. If granted an IN, students must complete the required work within a period of time stipulated by the instructor but not to exceed one year. After a year, the IN will be automatically changed into an F or the contingency grade.

YC (year course): a mark given at the end of the first term of a course in which the full year of work must be completed before a qualitative grade is assigned. The grade given at the end of the second term is the grade for the entire course.

CP (credit pending): given only in graduate research courses in which student research projects regularly extend beyond the end of the term. Upon completion, a final qualitative grade is then assigned and credit allowed. The mark of CP implies satisfactory progress.

MU (make-up examination): given to a student who has failed the final examination in a course but who has been granted the privilege of taking a second examination in an effort to improve their final grade. The privilege is granted only when there is a wide discrepancy between the quality of the student’s work during the term and their performance on the final examination, and when, in the instructor’s judgment, the reasons justify a make-up examination. A student may be granted the mark of MU in only two courses in one term, or, alternatively, in three or more courses in one term if their total point value is not more than 7 credits. The student must remove MU by taking a special examination administered as soon as the instructor can schedule it.

P/F (pass/fail): Undergraduates may select to take only one course that is offered for a letter grade pass/fail each semester. In general, courses taken pass/fail do not count toward degree requirements including the 128-point requirement. There are two exceptions to this rule. Physical Education classes do count toward the 128 point requirement, even though students do not receive letter grades for the class. Additionally, undergraduate students may take up to two courses of the 9-11 nonteaching elective credit on a P/F basis. These courses must be at the 3000-level or higher and must be courses that can be taken P/F by students attending Columbia College (e.g., instruction classes in foreign language and core curriculum classes are not eligible to be taken pass/fail). These courses may not count toward the minor. Students have until the end
of the change of program period the next semester (or June 1 for graduating students) to uncover the P/F for a letter grade. Students may take only one class P/F per semester to count toward the 128 points, exclusive of physical education credit and any other course that is taught only on a P/F basis. Please note that physical education classes are the only courses taught solely on a P/F basis that may apply toward the 128 credits for the degree. The P/F option does not count toward degree requirements for graduate students and cannot be uncovered under any circumstances.

W (official withdrawal): a mark given to students who are granted a leave of absence after the drop deadline for the semester. The grade of W, meaning “official withdrawal,” will be recorded as the official grade for the course in lieu of a letter grade. The grade of W will zero out the credits for the class so the student’s GPA will not be affected.

Name Changes
Columbia University recognizes that some students prefer to identify themselves by a First Name and/or Middle Name, other than their Legal Name. For this reason, beginning in the Spring 2016 semester, the University has enabled students to use a “Preferred Name” where possible in the course of University business and education.

Under Columbia’s Preferred Name policy, any student may choose to identify a Preferred First and/or Middle Name in addition to the Legal Name. Students may request this service via a link on SSOL. The student’s Preferred Name may be used in many University contexts, including SSOL, class rosters, CourseWorks, and Canvas, and on ID Cards. For some other records, the University is legally required to use a student’s Legal Name. However, whenever reasonably possible, a student’s "Preferred Name" will be used. Please see registrar.columbia.edu/content/name-and-address-changes for further details.

Students may change their name of record by submitting a name change affidavit to the Student Service Center. Affidavits are available from this office or online at registrar.columbia.edu.

GRADUATION
Columbia University awards degrees three times during the year: in February, May, and October. There is one Commencement ceremony in May.

Application or Renewal of Application for the Degree
In general, students can download an application for the degree from the Registrar’s website and file it according to the instructions on the form, or pick up and file it from their schools or departments, but there are several exceptions. Candidates for Master of Science degrees may pick up and file their application for the degree with the Diploma Division, 210 Kent Hall, or through the registrar’s website: registrar.columbia.edu/registrar-forms/application-degree-or-certificate. Candidates for doctoral and Master of Philosophy degrees should inquire at their departments but must also follow the instructions of the Dissertation Office, 107 Low Library.

Diplomas
There is no charge for the preparation and conferral of an original diploma. If your diploma is lost or damaged, there will be a charge of $100 for a replacement diploma. Note that replacement diplomas carry the signatures of current University officials. Applications for replacement diplomas are available on the Registrar’s website: registrar.columbia.edu/registrar-forms/application-replacement-diploma. Any questions regarding graduation or diploma processing should be addressed to diplomas@columbia.edu.

General deadlines for applying for graduation are November 1 for February, January 1 for May, and August 1 for October. (When a deadline falls on a weekend or holiday, the deadline moves to the next business day.) Doctoral students must deposit their dissertations two days before the above conferral dates in order to graduate.

Students who fail to earn the degree by the conferral date for which they applied must file another application for a later conferral date.
ACADEMIC HONORS

Dean’s List
To be eligible for Dean’s List honors, an undergraduate student must achieve a grade-point average of 3.5 or better and complete at least 15 graded credits with no unauthorized incompletes, UWs, or grades lower than C.

Honors Awarded with the Degree
At the end of the academic year, a select portion of the candidates for the Bachelor of Science degree who have achieved the highest academic cumulative grade-point average are accorded Latin honors. Latin honors are awarded in three categories (cum laude, magna cum laude, and summa cum laude) to no more than 25 percent of the graduating class, with no more than 5 percent summa cum laude, 10 percent magna cum laude, and 10 percent cum laude. Honors are awarded on the overall record of graduating seniors who will have completed a minimum of four semesters at Columbia upon graduation. Students who enter Columbia through the Combined Plan program are eligible for honors based on three semesters at Columbia. Students may not apply for honors.

ACADEMIC MONITORING

The SEAS Faculty Committee on Instruction determines academic policies and regulations for the School.

The Undergraduate Committee on Academic Standing is expected to uphold the policies and regulations of the Committee on Instruction and determine when circumstances warrant exceptions to them.

Academic performance is reviewed by advisers at the end of each semester. The Undergraduate Committee on Academic Standing, in consultation with the departments, meets to review undergraduate grades and progress toward the degree. Indicators of academic well-being are grades that average above 2.0 each term, in a coordinated program of study, with no incomplete grades.

Possible academic sanctions include:

• Warning: C– or below in any core science course or in a required course for their major; low points toward degree completion
• Academic Probation: Students will be placed on academic probation if they meet any of the conditions below:
  – fall below a 2.0 GPA in a given semester
  – have not completed 12 points successfully in a given semester
  – have not completed chemistry, physics, University Writing, The Art of Engineering, and calculus during the first year
  – receive a D, F, UW, or unauthorized Incomplete in any first-year/sophomore required courses
  – receive a D, F, UW, or unauthorized Incomplete in any course required for the major
  – receive straight C’s in the core science courses (chemistry, calculus, physics) or in required courses for their major
  – not making significant progress toward the degree
• Continued Probation: Students who are already on probation and fail to meet the minimum requirements as stated in their sanction letter.
• Strict Probation: Students who are already on probation, fail to meet the minimum requirements as stated in their sanction letter, and are far below minimum expectations. This sanction is typically applied when there are signs of severe academic difficulty.
• Suspension and Dismissal: Students who have been placed on academic probation and who fail to be restored to good academic standing in the following semester can be considered either for suspension or dismissal by the Undergraduate Committee on Academic Standing. The decision to suspend or dismiss a student will be made by the Committee on Academic Standing in the Berick Center for Student Advising and the Dean’s Office in close consultation with the student’s departmental adviser when the student has declared a major. In cases of suspension, the student will be required to make up the deficiencies in their academic record by taking appropriate courses at a four-year accredited institution. Students must be able to complete their degree requirements in their eighth semester at Columbia after readmission. If this is not achievable, then students should be considered for dismissal instead.

The courses that the student must take will be determined by the Undergraduate Committee of Academic Standing and by the student’s departmental adviser when the student has declared a major. All
proposed courses will be reviewed by the appropriate faculty who teach the equivalent classes at Columbia University. All courses that are being taken to fulfill a major requirement or as a technical elective must be approved by the student’s departmental adviser. Courses being taken to count as a nontech elective or to count as general credit would only require the approval of the Undergraduate Committee on Academic Standing. The existing procedures for the approval of outside credit will be followed in these cases. Students must receive a grade of B or better for the credit to be transferred.

The Office of Graduate Student Affairs monitors the academic progress of graduate students in consultation with the departments. Students will be placed on Academic Probation if their cumulative GPA is below 2.5 or minimum GPA required by the academic department, whichever is higher. Students who are on Academic Probation and do not return to good standing after one semester may be dismissed from the program.

**VOLUNTARY MEDICAL LEAVE OF ABSENCE**

A voluntary medical leave of absence for an undergraduate student is granted by the James H. and Christine Turk Berick Center for Student Advising to an undergraduate student whose health prevents them from successfully pursuing full-time study. Undergraduates who take a voluntary medical leave of absence are guaranteed housing upon their return if they were already guaranteed housing.

A voluntary medical leave of absence for a graduate student is granted by the Office of Graduate Student Affairs, so please consult with this office for more information.

Documentation from a physician or counselor must be provided before such a leave is granted. In order to apply for readmission following a voluntary medical leave, a student must submit proof of recovery from a physician or counselor. Graduate students may also be required to meet with a medical provider at Columbia. Doctoral students must have a faculty adviser and funding from their faculty adviser and/or academic department prior to and returning from an approved voluntary medical leave.

A voluntary medical leave of absence for an undergraduate student is for a minimum of one year and cannot be longer than two years. A voluntary medical leave for a graduate student is for a minimum of one semester, up to two years. If the student does not return within the two-year time frame, they will be permanently withdrawn from the School. Students may only return in the fall or spring term, not in summer sessions.

When a voluntary medical leave of absence is granted during the course of the semester, the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be W (official withdrawal) in all courses. In certain circumstances, a student may qualify for an incomplete, which would have to be completed by the first week of the semester in which the student returns to Columbia. If the Incomplete is not completed by that time, a W will be inserted as the final grade.

In exceptional cases, an undergraduate student may apply for readmission following a one-term voluntary medical leave of absence. In addition to providing a personal statement and supporting medical documentation for the voluntary medical leave readmission committee to review, the student will also need to provide a well-developed academic plan that has been approved by the departmental adviser and the Berick Center for Student Advising as part of the readmission process. This plan must demonstrate that their return to Columbia Engineering following a one-semester leave of absence will allow the student to properly follow the sequence of courses as required for the major and to meet all other graduation requirements. Students must apply for readmission from a medical leave by November 1 for the fall semester and June 1 for the spring semester. The final decision regarding whether or not a student will be allowed to be readmitted after a medical leave will be made by the Medical Leave Readmission Committee. Students should consult the medical leave policy statement available on the website of the Berick Center for Student Advising for more information regarding the readmission procedures from medical leave.

A return from a voluntary medical leave request must be made before the start of the fall or spring semester. Graduate students may apply for readmission following a one-term voluntary medical leave of absence. As part of the readmission process, graduate students need to submit a personal statement and supporting medical documentation. Graduate students should contact the Office of Graduate Student Affairs for more information. The deadlines for petitioning a readmission are June 1 for the fall semester and November 1 for the spring semester. The deadlines for petitioning a return from a voluntary medical leave for graduate students after one semester are June 1 for the fall semester and November 1 for the spring semester. Students are not eligible to return from a medical leave during the summer.

During the course of the leave, students are not permitted to take any courses for the purpose of transferring credit and are not permitted to be on campus. For more information about the voluntary medical leave of absence policy, undergraduates should consult their CSA adviser; graduate students should consult the Office of Graduate Student Affairs.

**VOLUNTARY PERSONAL LEAVE OF ABSENCE**

A voluntary personal leave of absence (VPLOA) may be granted by the Committee on Academic Standing to undergraduate students who request a temporary withdrawal from Columbia Engineering for a nonmedical reason. Students considering a voluntary personal leave must discuss this option in advance with their CSA adviser. Voluntary leaves are granted for a period of one academic year only for undergraduate students; VPLOAs will ordinarily not be granted for one semester, or for more than one year. Students must be in good academic standing at the time of the leave and must be able to complete their major and degree in eight semesters.

A voluntary personal leave of absence for a graduate student is granted by the Office of Graduate Student Affairs. A graduate student must be registered for at least one semester and have a minimum cumulative 2.5
GPA to request a voluntary personal leave. Additionally, doctoral students must have a faculty adviser and funding from their faculty adviser and/or academic department prior to and returning from an approved voluntary personal leave of absence. The deadline to request a VPLOA for a given term is the last day to drop classes during that term. VPLOA requests made after the drop deadline will be denied. A graduate student may request to return from a voluntary personal leave of absence for the fall, spring, or summer semester. A request to return must be made before the semester starts. Please contact the Office of Graduate Student Affairs for more information.

When a voluntary personal leave of absence is granted during the course of the semester, the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be a W (official withdrawal) in all courses. In certain circumstances, a student may qualify for an incomplete, which would have to be completed by the first week of the semester in which the student returns to Columbia. If the Incomplete is not completed by that time, a W will be inserted as the final grade.

In exceptional cases, an undergraduate may apply for readmission following a one-term voluntary personal leave of absence. The student will need to provide to the Committee on Academic Standing a well-developed academic plan that has been approved by the departmental adviser and the Berick Center for Student Advising as part of the admission process. This plan must demonstrate that their return to Columbia Engineering following a one-semester personal leave of absence will allow the student to properly follow the sequence of courses as required for the major and to meet all other graduation requirements by their eighth semester. The Committee on Academic Standing will review the student’s academic plan and request for readmission. The deadlines for petitioning for readmission are June 1 for the fall semester and November 1 for the spring semester. Undergraduates should consult the medical leave policy statement available on the website of the Berick Center for Student Advising for more information regarding the readmission procedures from a voluntary personal leave of absence. The deadlines for petitioning a return from a voluntary personal leave for graduate students after one semester are June 1 for the fall semester and November 1 for the spring.

Students may not take courses for transferable credit while on leave. Finally, students who choose to take voluntary personal leaves are not guaranteed housing upon return to the University. International students should contact the International Students and Scholars Office to ensure that a leave will not jeopardize their ability to return to Columbia Engineering.

### Undergraduate Emergency Family Leave of Absence

Students who must leave the University for urgent family reasons that necessitate a semester-long absence (e.g., family death or serious illness in the family) may request an emergency family leave of absence. Documentation of the serious nature of the emergency must be provided. Students must request an emergency family leave of absence from their advising dean in the James H. and Christine Turk Berick Center for Student Advising.

When an emergency family leave of absence is granted during the course of the semester, the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be W (official withdrawal) in all courses. In certain circumstances, a student may qualify for an incomplete, which would have to be completed by the first week of the semester in which the student returns to Columbia. If the Incomplete is not completed by that time, a W will be inserted.

To return, students must notify the Berick Center for Student Advising as soon as possible, ideally by November 1 for the spring semester and June 1 for the fall semester. Students must request readmission in writing and submit a statement describing their readiness to return. Once readmission is granted, housing will be guaranteed upon their return if they were already guaranteed housing. SEAS students may request permission to return after one semester as long as they can demonstrate that they can remain in sequence with their coursework and have the prior approval of the departmental adviser.

Students who decide not to return must notify the James H. and Christine Turk Berick Center for Student Advising of their decision. The date of separation for the leave of absence will be the date of separation for withdrawal. Leaves may not extend beyond four semesters. Students who do not notify the Berick Center for Student Advising of their intentions by the end of the two-year period will be permanently withdrawn.

### Leave for Military Duty

Please refer to Military Leave of Absence Policy in Essential Policies for the Columbia Community (facets.columbia.edu) for recent updates regarding leave for military duty.

### Involuntary Leave of Absence Policy

Please refer to Involuntary Leave of Absence Policy in Essential Policies for the Columbia Community (facets.columbia.edu).

### Readmission

Students seeking readmission must submit evidence that they have achieved the purposes for which they left. Consequently, specific readmission procedures are determined by the reasons for the withdrawal. Further information for undergraduate students is available in the Berick Center for Student Advising. Graduate students should see the Office of Graduate Student Affairs.

Students applying for readmission should complete all parts of the appropriate readmission procedures by June 1 for the autumn term or November 1 for the spring term.
ACADEMIC INTEGRITY

Academic integrity defines a university and is essential to the mission of education. At Columbia, you are expected to participate in an academic community that honors intellectual work and respects its origins. The abilities to synthesize information and produce original work are key components in the learning process. As such, a violation of academic integrity is one of the most serious offenses that one can commit at Columbia. If found responsible, violations range from conditional disciplinary probation to expulsion from the University. Compromising academic integrity not only jeopardizes a student’s academic, professional, and social development, it also violates the standards of our community. As a Columbia student, you are responsible for making informed choices with regard to academic integrity both inside and outside the classroom.

Students rarely set out with the intent of engaging in violations of academic integrity. But classes are challenging at Columbia, and students may find themselves pressed for time, unprepared for an assignment or exam, or feeling that the risk of earning a poor grade outweighs the need to be thorough. Such circumstances lead some students to behave in a manner that compromises the integrity of the academic community, disrespects their instructors and classmates, and deprives them of an opportunity to learn. In short, they cheat. Students who find themselves in such circumstances should immediately contact their instructor and adviser for advice.

For undergraduate students, another resource is the Academic section of the Live Well | Learn Well site (wellbeing.columbia.edu/resources) for Academic resources and support.

The easiest way to avoid the temptation to cheat in the first place is to prepare yourself as best you can. Here are some basic suggestions to help you along the way:

• Discuss with each of your faculty their expectations for maintaining academic integrity.
• Understand that you have a student responsibility to uphold academic integrity based on the expectations outlined in each of your course syllabi.
• Understand instructors’ criteria for academic integrity and their policies on citation and group collaboration.
• Clarify any questions or concerns about assignments with instructors as early as possible.
• Develop a timeline for drafts and final edits of assignments and begin preparation in advance.
• Avoid plagiarism: acknowledge people’s opinions and theories by carefully citing their words and always indicating sources.
• Assume that collaboration in the completion of assignments is prohibited unless specified by the instructor.
• Utilize the campus resources, such as the Berick Center for Student Advising, Counseling and Psychological Services (CPS), and Graduate Student Affairs, if feeling overwhelmed, burdened or pressured.
• Attend Academic Integrity workshops offered throughout the academic year.
• If you suspect that an academic integrity violation may have occurred, know that you can talk to your instructor, Advising Dean, Director of Academic Integrity, Office of Graduate Student Affairs, or the Student Conduct and Community Standards Office to report any allegations of academic misconduct.

Students found responsible for an academic integrity violation may be ineligible to receive Latin Honors at Class Day or ineligible to take on leadership positions for a period of time and/or other distinctions.

Plagiarism and Acknowledgment of Sources

Columbia has always believed that writing effectively is one of the most important goals a college student can achieve. Students will be asked to do a great deal of written work while at Columbia; for instance: term papers, coding problem sets, seminar presentations, laboratory reports, and analytical essays of different lengths. These papers play a major role in course performance, but more importantly, they play a major role in intellectual development. Columbia’s academic integrity policy in the Standards & Discipline defines plagiarism as “the use of words, phrases, or ideas belonging to the student, without properly citing or
acknowledging the source, is prohibited. This may include, but is not limited to copying computer programs for the purposes of completing assignments for submission.”

One of the most prevalent forms of plagiarism involves students using information from the Internet without proper citation. While the Internet can provide a wealth of information, sources obtained from the web must be properly cited just like any other source. If you are uncertain how to properly cite a source of information that is not your own, whether from the Internet or elsewhere, it is critical that you do not hand in your work until you have learned the proper way to use in-text references, footnotes, and bibliographies. Faculty members or teaching assistants are available to help as questions arise about proper citations, references, and the appropriateness of group work on assignments. Students can also check with the Writing Center directly. Another option is to connect with Research Librarians who facilitate monthly citation management workshops online and in person. Information on these workshops is posted online on the Columbia Libraries website. Undergraduate students can also meet with the Director of Academic Integrity to review citation styles or options for academic support by emailing ugrad-integrity@columbia.edu. Graduate students can consult with the Office of Graduate Student Affairs in Suite 530 in Mudd.

Personal Responsibility, Finding Support, and More Information
A student’s education at Columbia University consists of two complementary components: a mastery over intellectual material within a discipline and the overall development of moral character and personal ethics. Participating in forms of academic dishonesty violates the standards of our community at Columbia and severely inhibits a student’s chance to grow academically, professionally, and socially. As such, Columbia’s approach to academic integrity is informed by its explicit belief that students must take full responsibility for their actions, meaning you will need to make informed choices inside and outside the classroom. Columbia offers a wealth of resources to help students make sound decisions regarding academics, extracurricular activities, and personal issues. Undergraduate students should consult an advising dean or meet with the Director of Academic Integrity in Suite 601 in Lerner Hall. Graduate students should consult the Office of Graduate Student Affairs in Suite 530 in Mudd.

Academic Integrity Policies and Expectations
Violations of policy may be intentional or unintentional and may include dishonesty in academic assignments or in dealing with University officials, including faculty and staff members. Moreover, dishonesty during the Dean’s Discipline hearing process may result in more serious consequences.

Types of academic integrity violations:

- Academic Dishonesty, Facilitation of: assisting another student in a violation of academic integrity is prohibited. This may include but is not limited to selling and/or providing notes, exams, and papers.
- Assistance, Unauthorized Giving: unauthorized assistance to another student or receiving unauthorized aid from another person on tests, quizzes, assignments, or examinations without the instructor’s express permission is prohibited.
- Bribery: offering or giving any favor or thing of value for the purpose of improperly influencing a grade or other evaluation of a student in an academic program is prohibited.
- Cheating: wrongfully using or attempting to use unauthorized materials, information, study aids, or the ideas or work of another in order to gain an unfair advantage is prohibited. Cheating includes, but is not limited to, using or consulting unauthorized materials or using unauthorized equipment or devices on tests, quizzes, assignments, or examinations, working on any examination, text, quiz, or assignment outside the time constraints imposed, the unauthorized use of prescription medication to enhance academic performance, and/or submitting an altered examination or assignment to an instructor for regrading.
- Collaboration, Unauthorized: collaborating on academic work without the instructor’s permission is prohibited. This includes, but is not limited to, unauthorized collaboration on tests, quizzes, assignments, labs, and projects.
- Dishonesty: falsification, forgery, or misrepresentation of information to any University official in order to gain an unfair academic advantage in coursework or lab work, on any application, petition, or documents submitted to this University is prohibited. This includes, but is not limited to, falsifying information on a resume, fabrication of credentials or academic records, misrepresenting one’s own research, providing false or misleading information in order to be excused from classes or assignments, and/or intentionally underperforming on a placement exam.
- Ethics, Honor Codes, and Professional Standards, Violation of: any violation of published institutional policies related to ethics, honor codes, or professional standards of a student’s respective school is prohibited.
- Failing to Safeguard Work: failure to take precautions to safeguard one’s own work is prohibited.
- Giving or Taking Academic Materials, Unauthorized: unauthorized circulation or sharing of past or present course material(s) without the instructor’s express permission is prohibited. This includes, but is not limited to, assignments, exams, lab reports, notebooks, and papers.
- Obtaining Advanced Knowledge: unauthorized advanced access to exams or other assignments without an instructor’s express permission is prohibited.
- Plagiarism: the use of words, phrases, or ideas belonging to another without
properly citing or acknowledging the source is prohibited. This may include, but is not limited to, copying computer programs for the purposes of completing assignments for submission.

• Sabotage: inappropriately and deliberately harming someone else’s academic performance is prohibited.

• Self-Plagiarism: using any material portion of an assignment to fulfill the requirements of more than one course without the instructor’s express permission is prohibited.

• Test Conditions: violations of compromising a testing environment or violating specified testing conditions, to intentionally or unintentionally create access to an unfair advantage for oneself or others is prohibited.

DISCIPLINARY PROCEDURES

Many policy violations that occur in the Residence Halls or within fraternity and sorority housing are handled by the Office of Residential Life. More serious offenses are referred directly to Student Conduct and Community Standards. Violations in University Apartment Housing are handled by building managers and housing officials. Some incidents are referred directly to the School’s housing liaison in the Office of Graduate Student Affairs.

In matters involving rallies, picketing, and other mass demonstrations, the Rules of University Conduct outlines procedures.

Student Conduct and Community Standards is responsible for all disciplinary affairs concerning undergraduate students that are not reserved to some other body. The Office of Graduate Student Affairs is responsible for all disciplinary affairs concerning graduate students that are not reserved to some other body.

Students found responsible for reportable violations of conduct, including academic integrity violations, may face reports of such offenses on future recommendations for law, medical, or graduate school. Students found responsible for any violations of conduct may be disqualified from receiving Latin Honors or other awards. They may also be disqualified from participating in internships or other leadership roles. The parents or guardians of undergraduate students may also be notified.

Dean’s Discipline Process for Undergraduate and Graduate Students

It is expected that all students act in an honest way and respect the rights of others at all times. Dean’s Discipline is the process utilized to investigate and respond to allegations of behavioral or academic misconduct. The Dean’s Discipline process is not meant to be an adversarial or legal process, but instead aims to educate students about the impact their behavior may have on their own lives as well as on the greater community.

The process is initiated when an allegation is reported that a student may have violated University policies. Students may be subject to Dean’s Discipline for any activity that occurs on or off campus that impinges on the rights of other students and community members. This also includes violations of local, state, or federal laws.

Student Conduct and Community Standards is responsible for administering the Dean’s Discipline disciplinary process for all disciplinary affairs concerning students that are not reserved to some other body.

Students are expected to familiarize themselves with the Standards and Discipline handbook and the policies and expectations available on the Students Conduct and Community Standards website (studentconduct.columbia.edu), which is part of the required Academic Integrity Tutorial modules in CourseWorks. The Bulletin is also not to be considered the sole or comprehensive guide to policies at Columbia. Students should consult the policies and expectations of the various offices and departments for additional guidance.

Students found responsible for reportable violations of conduct, including academic integrity violations, will need to report of such offenses on future recommendations for law, medical, or graduate school. Students found responsible for any violations of conduct may be disqualified from receiving a sanctioned outcome of Disciplinary Probation or higher.

For more information about the discipline process for undergraduate students, please review the Academic Integrity website or Student Conduct & Community Standards. For more information about the discipline process for graduate students, please contact the Office of Graduate Student Affairs.

Confidentiality

Privacy and Reporting: Disciplinary proceedings conducted by the University are subject to the Family Education Rights and Privacy Act ("FERPA," also called "The Buckley Amendment"). There are several important exceptions to FERPA that will allow the University to release information to third parties without a student’s consent. For example, the release of student disciplinary records is permitted without prior student consent to University officials with a legitimate educational interest such as a student’s academic adviser and to Columbia Athletics if the student is an athlete. The University will also release information when a student gives written permission for information to be shared. To obtain a FERPA waiver, please visit: columbia.edu/cu/studentconduct/documents/FerpaRelease.pdf. To read more about the exceptions that apply to the disclosure of student records information, please visit: the University Policies Website at universitypolicies.columbia.edu/.
Directory of University Resources
Mathematics
410 Mathematics, MC 4426
212-854-2432

Physics
704 Pupin, MC 5255
212-853-1320

Statistics
1255 Amsterdam Avenue
Room 1005 SSW, MC 4690
212-851-2132

OMBUDS OFFICE
660 Schermerhorn Ext., MC 5558
212-854-1234
ombuds@columbia.edu
ombuds.columbia.edu/

On Wednesdays the Ombuds Officer is at the Columbia Medical Center office:
154 Haven Ave. Room 412
212-304-7026

PROFESSIONAL DEVELOPMENT AND LEADERSHIP
255 Engineering Terrace
646-761-1694
pdl-seas@columbia.edu
pdl.engineering.columbia.edu

PUBLIC SAFETY
101 Low Library, MC 4301
212-854-2797 (24 hours a day)
publicsafety@columbia.edu
publicsafety.columbia.edu

Campus Emergencies:
212-854-5555

Escort Service:
212-854-SAFE (7233)

REGISTRAR
210 Kent, MC 9202
registrar@columbia.edu
registrar.columbia.edu

STUDENT CONDUCT AND COMMUNITY STANDARDS
800 Watson Hall
612 West 115 Street, MC 2611
212-854-6872
studentconduct@columbia.edu
studentconduct.columbia.edu

STUDENT SERVICE CENTER
210 Kent, MC 9202
212-854-4400
ssc@columbia.edu
ssc.columbia.edu

UNIVERSITY LIFE
212-853-1628
UniversityLife@columbia.edu
universitylife.columbia.edu

WELLNESS
Engineering Graduate Wellness:
530 Mudd
212-854-6438
seas-wellness@columbia.edu
wellness.engineering.columbia.edu

Undergraduate Wellness:
Stephanie King
605 Lerner
212-853-1369
sk3296@columbia.edu
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Academic Calendar 2022–2023

The following Academic Calendar was correct and complete when compiled; however, the University reserves the right to revise or amend it, in whole or in part, at any time. Information on the current Academic Calendar may be obtained in the Student Service Center, 205 Kent, 212-854-4330, or visit registrar.columbia.edu.

FALL TERM 2022

August
21–25, Sept. 2–3 Registration by appointment (undergraduate)
25–Sept. 9 Graduate orientation and graduate department orientations
29–Sept. 5 New Student Orientation Program
30–Sept. 1 Registration by appointment (graduate)

September
1 Last Day to apply for October degrees
5 Labor Day, University holiday
6 First day of classes
6–16 Change of program by appointment (weekdays)
16 Last day to (1) register for academic credit, (2) change course programs, (3) submit written notice of withdrawal from the fall term to the Dean of Student Affairs for full refund of tuition and special fees, (4) drop Core Curriculum classes. No adjustment of fees for individual courses dropped after this date.
30 Last day to confirm, update, or request a waiver from the Student Medical Insurance Plan.

October
19 October degrees conferred
20 Birthday of Martin Luther King Jr., University holiday
21 First day of classes
21–27 Change of program by appointment (weekdays)
27 Deadline to add spring courses

November
8 February degrees conferred

December
1 Last day to apply for May degrees
12 Last day of classes
13–15 Study days
16–23 Final examinations
24–Jan. 16 Winter recess

SPRING TERM 2023

January
4–10, 15–14 Registration by appointment (undergraduate and graduate)
TBA Graduate orientation
16 Birthday of Martin Luther King Jr., University holiday
17 First day of classes
17–27 Change of program by appointment (weekdays)
27 Deadline to add spring courses

February
8 February degrees conferred

March
6 Midterm data
13–17 Spring recess
23 Last day to drop Engineering courses without academic penalty. Last day to change grading option

April
18–22 Registration by appointment for fall 2023

May
1 Last day of spring classes
2–4 Study days
5 Last day for continuing students to apply for financial aid for the 2023–2024 academic year
5–12 Final exam period for spring courses
15–17 Class Day and University Commencement will take place during this week (specific dates to be announced).

Photography:

Superimposed over this image is the emblem of the School’s vision, Columbia Engineering for Humanity.