School’s vision, Columbia Engineering for Humanity. Superimposed over this image is the emblem of the living parts of their wings. Specialized behaviors and wing scales to protect the living parts of their wings. Nanfang Yu and Cheng-Chia Tsai. Butterflies have specialized behaviors and wing scales to protect the living parts of their wings. Superimposed over this image is the emblem of the School’s vision, Columbia Engineering for Humanity.
Welcome to Columbia University’s Fu Foundation School of Engineering and Applied Science.

As students here, you are among the very best and brightest of your generation. Together with a talented group of students from around the world, you are embarking on a course of study that will enable you to become the next generation of leaders—leaders with a foundation in engineering.

Today, engineering is a foundational degree. The breadth and depth of our curriculum and course offerings prepare students for a wealth of pursuits in engineering and applied science and also provide a launch into 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, and processes to make life better.

Our first dean, Charles Frederik 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.

Today, our faculty and students continue to bring their curiosity, creative drive, entrepreneurial energy, and an innovative engineering mindset to some of the biggest challenges of our time. We have a school vision—Columbia Engineering for Humanity—that encapsulates our efforts to make a positive impact on society. It highlights the innovative and interdisciplinary work that our faculty and students are engaged in to create a more sustainable, healthy, secure, connected, and creative world.

As you prepare for a new academic year, we urge you to reflect on this vision and embrace the many opportunities afforded to you by a world-class 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,

Mary C. Boyce
Dean of Engineering
Morris A. and Alma Schapiro Professor
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Academic Calendar (see inside back cover)
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."

THE GILDED AGE
As the city grew, so did the School. King's College was rechartered as Columbia College in 1824 and relocated from the Wall Street area to what is now Midtown in 1857. Students began entering the new School of Mines in 1864. Trained in mining, mineralogy, and engineering, Columbia graduates continued to make their mark both at home and abroad. Working around the globe, William Barclay Parsons, Class of 1882, was an engineer on the Chinese railway and the Cape Cod and Panama Canals. Most important for New York, he was chief engineer of the city's first subway. Parsons continued to make his mark both at home and abroad.

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' 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 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 expansive "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, and Columbia Business School, 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 used 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 Biological Technology Accelerator (BioMedX), powered by NYU’s NYC Media Lab Combine program, the COSMOS Wireless Testbed, the Columbia IBM-Center for Blockchain and Data Transparency, and 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 interdisciplinary educational environment within the School. Some of these programs and centers have helped propel the School’s modernization efforts, including personalized robotics for use in physical rehabilitation and an initiative to develop a laboratory space for 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 connect students, faculty, and students about the many aspects involved in commercializing biomedical innovation.

Entrepreneurship remains an important cultural current 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.

For alumni, entrepreneurial support continues. The Columbia Startup Lab, a coworking facility located in SoHo, provides subsidized space for Columbia alumni entrepreneurs to move their ventures off-faculty and nurture their fledging ventures. The Lab is the result of a unique partnership between the School of Engineering and Applied Science 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 and sciences is invaluable, programming provides the surest chart with which an engineer can navigate the future, all undergraduates must complete a core curriculum that is both rich with the cultural crossroads of the world. New York, the major city in the world, offers an entrepreneurial and inventive energy that an engineer can navigate the future, even in the context of the world’s largest population centers and 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 non-technical aspects of the curriculum, all Columbia Engineering students—past, present, and future—gain the humanistic tools needed to do more than simply technical innovations, 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 faculty members and the support 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 the City of New York. Within easy reach by walking, bus, subway, or bike, New York’s broad range of social, cultural, and business communities offer an unparalleled 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, present-day New York provides the surest chart with which an engineer can navigate the future. 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 located in Harlem 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 within 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 opportunities for exposure to 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, construction, 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 in the United States: the main campus in Manhattan, the Columbia Nano Initiative, and advanced research installations, such as the Columbia Genome Center and the Columbia Nano Initiative, established to serve as the hub of multidisciplinary and collaborative research programs in nanoscale science and engineering. Shared facilities and equipment to support nanoscale science and engineering research include a state-of-the-art clean room in the Schickar Center for Photonic and Quantum Sensing Research (CPSQR) and a Transmission Electron Microscope (TEM) Laboratory on the campus of the College of Physicians and Surgeons, 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 relocates to this campus by 2021, and plans are underway to develop a new building here for Columbia Engineering, as well. These spaces house both basic science research and teaching in brain science, an art gallery, screening room, and performance spaces, and space for active community engagement.

COLUMBIA ENGINEERING Columbia University (The Fu Foundation School of Engineering and Applied Science) occupies four laboratory and classroom buildings at the north end of the Columbia University campus, including the Northwest Corner Science and Engineering Building, the Korman Innovation Laboratory, the Graduate School of Arts and Science’s Edward H Sanders Science Center, and the NASA Goddard Institute for Space Studies located just off the Morningside campus.

THE MORGANSTADT HEIGHTS CAMPUS
Columbia Engineering is located on Columbia’s Morningside campus. One of the handiest urban institutions in the country, the 13.1 million square foot campus reaches 200 feet above the street level and is bounded by Morningside Heights, and the Manhattanville campus is the newest addition to Columbia University’s roster of environmentally sustainable campuses, and will grow over the next decade to encompass more than 17 acres. Further west on Washington Heights is the Manhattanville campus.

From Broadway and 125th Street West to a revitalized Hudson River waterfront, the Manhattanville campus is a welcoming environment of publicly accessible open space, and community-friendly and innovative 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 relocates to this campus by 2021, and plans are underway to develop a new building here for Columbia Engineering, as well. These spaces house both basic science research and teaching in brain science, an art gallery, screening room, and performance spaces, and space for active community engagement.

Columbia Engineering Computing Facilities The CECF provides a full set of professional-grade engineering software tools and a collaborative classroom learning environment.

The lab is utilized in some of the School’s introductory first-year engineering projects, as well as advanced courses in the fields of 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 computer-aided design, physical prototyping, fabric arts, woodworking, 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.
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 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. Students in the Art of Engineering choose a half-semester, hands-on project in one of the School’s nine undergraduate engineering disciplines, followed by a half-semester general project that changes each year. Depending on the project chosen, students will solder, 3D print, laser cut, simulate, design websites, and much more. These skills are further developed as students progress toward their senior year projects. Since the fall of 2014, Columbia Engineering students have been able to utilize the School’s brand new MakerSpace, a collaborative environment where students can learn, explore, experiment, and create prototypes. While pursuing their own interests, undergraduate students are encouraged to participate in a broad range of engaging faculty research projects established by the Student Research Program. Students can apply for available research positions in Columbia Labs through the website at studentresearch.engineering.columbia.edu. 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 diverse, culturally rich 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
ccsa@columbia.edu

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, exploration, 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 advisor from the Berick Center for Student Advising for the duration of his or her undergraduate career. Generally, each matriculating student is assigned to an advising dean, who is a liaison to the department the student indicated as his or her first intended major on the Columbia application. When a student declares a major, a faculty member is also appointed to advise him or her 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 advisors work closely with other CSA advisors 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 the 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 course 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 thoughtfully, critically, and imaginatively 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 advisors.

• 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 CC1101: University writing (3 points)

2. One of the following two-semester sequences, (followed by COGS CC1001-CC1102: 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

COGS CC1101-CC1102: Introduction to contemporary civilization in the West or Global Core: Any 2 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 (6–11 points of credit)

The following course listing by department specifies the Columbia College, Barnard, or Columbia Engineering courses that other students do not fulfill the nontechnical requirement.

AFRICAN-AMERICAN STUDIES: All courses

AMERICAN STUDIES: All courses

ANCIENT STUDIES: All courses

ANTHROPOLOGY: All courses in sociocultural anthropology

All courses in archaeology except field work

No courses in biological/physical anthropology

UN1011, UN1024, UN594,
GU147, UN148, UN4200, UN4700

ARCHITECTURE: No course

ART HISTORY AND ARCHAEOLOGY: 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

ENGINEERING 2020-2021

THE UNDERGRADUATE PROGRAMS
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 UN1004 with grade of C or better</td>
</tr>
<tr>
<td>Computer Science</td>
<td>4 or 5</td>
<td>3</td>
<td>Requires completion of CSCI UN2064 with grade of C or better</td>
</tr>
<tr>
<td>Economics</td>
<td>4 or 5</td>
<td>3</td>
<td>Exemption from COMS W1004</td>
</tr>
<tr>
<td>Spanish Language and Literature</td>
<td>5 and 4</td>
<td>4*</td>
<td>Exemption from ECON UN1105. Exams must be taken in both micro and macro, with a score of 5 in one and at least 4 in the other.</td>
</tr>
<tr>
<td>English Language and Composition</td>
<td>5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>French Language and Composition</td>
<td>4 or 5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>German Language</td>
<td>4 or 5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>Government and Politics</td>
<td>United States Co-Comparative</td>
<td>5</td>
<td>4*</td>
</tr>
<tr>
<td>History</td>
<td>European</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Italian Language</td>
<td>4 or 5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>Latin Language</td>
<td>5</td>
<td>3</td>
<td>No exemption</td>
</tr>
<tr>
<td>Mathematics</td>
<td>Calculus AB</td>
<td>4 or 5</td>
<td>3</td>
</tr>
<tr>
<td>Calculus BC</td>
<td>4</td>
<td>3</td>
<td>Requires completion of MATH UN1101 with a grade of C or better. 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. 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>C-EM</td>
<td>4 or 5</td>
<td>3</td>
</tr>
<tr>
<td>C-NEC</td>
<td>4 or 5</td>
<td>3</td>
<td>Requires completion of PHYS UN1401 or 1601. Credit is reduced to 0 if PHYS UN2001 is taken and the final grade is C- or lower.</td>
</tr>
<tr>
<td>Spanish Language</td>
<td>4 or 5</td>
<td>3</td>
<td>No exemption. Both AP Spanish 1 and 2 must be taken to receive credit.</td>
</tr>
</tbody>
</table>

The majority of the activities are offered in ten time preferences. Additionally, there are early morning, evening, and Friday classes. 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.

The AP credit chart is designed to allow students to take courses during the summer term at a local or off-campus institution with the approval of the department or the office of Student Advising. Students must register for one section of introductory courses each term.

Advanced Placement

Prior to entering Columbia, students may have taken Advanced Placement examinations through the College Board. Exams may be taken in a number of technical and non-technical 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 exemptions. CEEB advanced placement credit is added to the Columbia transcript, and grades are factored into students' GPAs. Students whose secondary school work was in other national systems, such as the French Baccalauréat, may be granted credit in certain disciplines for high scores. The appropriate transcript should be submitted to the James H. and Christine Turk Berick Center for Student Advising, 403 Lerner.

Eligibility Requirements

In order to participate in the semester-long or yearlong study abroad program, students must:

• Be an enrolled student in good academic and disciplinary standing
• Have at least a 3.0 GPA
• Be making adequate progress toward finishing the first and second year requirements
• Have declared a major

Eligibility Requirements

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

Eligibility Requirements

For Summer Study Abroad
• Have at least a 3.0 GPA
• still eligible for financial aid
• Not eligible for financial aid

Eligibility Requirements

For Winter/Spring Study Abroad
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Approved from their department prior to departure on a study-abroad program.

**Deadlines**
- **Spring trips:** October 1st
- **Fall trips:** March 1st
- **Summer trips:** May 1st
- **Year-long trips:** March 1st

For more information on study abroad, students should contact:

- Center for Undergraduate Global Engagement
  600 Kent Hall, MC 2484
  1140 Amsterdam Avenue
  New York, NY 10027
  212-854-2059
  uge.columbia.edu

- SEAS Undergraduate Student Affairs
  seasstudyabroad@columbia.edu

**COMBINED PLAN PROGRAMS**

**Undergraduate Admissions**
212 Hamilton Hall, 212-854-2222
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 consecutive 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. Each affiliated school has a liaison officer who coordinates the program at his or her 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 25 for Information on the 4-2 Master of Science Program, which is administered through the Office of Undergraduate Student Affairs.

**THE JUNIOR-SENIOR PROGRAMS**

Students who wish to apply for a double 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 for alternative courses for duplicate requirements.

3-2 students are not eligible to have a second major due to 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 Schenck, Jr., and, of course, Harvey Sibley Mood.

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 credit 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, major departmental requirements, and technical and nontechnical elective requirements. Students who wish to transfer points of credit may count no more than 6 transfer points toward the degree and must satisfy the University’s residence requirements by taking at least 30 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 all minors are not, and cannot, be 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. Therefore, 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 203-208.

PROGRAMS IN PREPARATION FOR OTHER PROFESSIONS

James H. and Christine Turk Berick Center for Student Advising

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 an engineering field. In an increasingly technological society, the line between humanities and sciences is blurred. Students can 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 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 volun- teer and research opportunities across New York City and beyond. Exploration of the career and sustained interactions with patients is vital by many medi- cal schools as essential preparation and therefore students are strongly encour- aged to spend time volunteering/work- ing 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 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 com- mon) 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 attend 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 advisor in the Berick Center for Student Advising. This program is selective, and admission is based on the following factors: grading of the B.S. at Columbia University in the fourth year; fulfillment of the 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, the student needs 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

Undergraduate Admissions

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 33-36 credits of points required in the elementary education program.

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**TUITION**

Undergraduate students enrolled in The Fu Foundation School of Engineering and Applied Science pay a flat tuition charge of $30,049 per term, regardless of the number of course credits earned. Postgraduate special students and degree candidates enrolled for a ninth term are billed according to the per-point system; the per-point cost is $2,008.

**MANDATORY FEES**

- **Orientation fee:** $448 (one-time charge in the first term of registration)
- **Student Life fee:** On-campus students: $623 fall / $608 spring
  - Remote students: $501 fall / $506 spring
- **Health and Related Services fee:** $610 per term
- **International Services charge:** $110 per term
- **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
- **Books and course materials:** Depending upon course
- **Laboratory fees:** See course listings
- **Room and board (estimated):** $15,130

**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, costs, 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 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 his or her 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.

**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**

Promoted for calendars of a different duration:

<table>
<thead>
<tr>
<th>Duration</th>
<th>1st week</th>
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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 his or her school or program at the time SAP is assessed. The SAP policy may be found online at sfs.columbia.edu/central-sap-policy.
engineering programs

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 typically 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 Master of Science degree) will be allowed for such subjects. Accordingly, Master of Science programs may include from 5 to 8 points and may require three terms for completion. Doctoral research credits cannot be used toward the M.S. degree requirements.

All degree requirements must be completed within five years of the beginning of graduate study. Under extraordinary circumstances, a written request for an extension of this time limit may be submitted to the student's department for approval by the department chair and the Assistant Dean. A minimum cumulative grade-point average of 2.5 is required for the M.S. degree. A student who, at the end of any term, has not attained the grade-point average required for the degree may be asked to withdraw. After the first semester of readmission, an M.S. student must submit an application to apply and transfer to another academic program if the student is not successful with the application process, then he or she must make sure requirements for the original academic program are completed.

Professional Development Leadership M.S. Requirement (ENG E4000)

The Professional Development and Leadership (PDL) program educates students to maximize performance and achieve their full potential as engineering leaders. The core modules focus on development of professional skills and competencies necessary to succeed in a fast-changing technical climate. M.S. students must complete the professional development and leadership course, ENG E4000, as a graduation requirement.

Professional Development Leadership Ph.D. Requirement (ENG E6001-6004)

The Professional Development and Leadership (PDL) program educates students to maximize performance and achieve their full potential during and after the doctoral program. The goal is to cultivate future scholars and leaders in their respective fields. The modules are tailored for each student's doctoral program with a focus on the development of academic, research, and professional skills. Ph.D. candidates are strongly encouraged to complete ENG E6001-6004 and should consult their program for 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, computer science, Earth and environmental, electrical, industrial, and mechanical engineering; applied physics; applied mathematics; 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 will be individually designed in consultation with a faculty advisor and will integrate undergraduate coursework 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 Sciences, 503 S.W. Mudd, 4718, 500 West 120th Street, New York, NY 10027; you should also contact your host institution’s Combined Plan liaison for program information. You may, in addition, email questions to seasgrad@columbia.edu.

Certificate of Professional Achievement in Data Science

Graduate students are also eligible 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, and Machine Learning for Data Science, and Exploratory Data Analysis and Visualization.

Joint Program with the School of Business in Industrial Engineering

The Graduate School of Business 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 in Data Science

Candidates for the Master of Science in Data Science are required to complete a minimum of 30 graduate-level credit hours, 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, the opportunity for students for Data Science, and Data Science Capstone & Ethics. A minimum of 9 credits of elective credits is required. The program will consist of basic undergraduate courses during the first year, of graduate courses in the selected field. The student must complete at least 30 credits of graduate study to qualify for the degree. Students admitted to graduate study on a part-time or full-time basis may be allowed to take a required subject at another school. Under special conditions, and with the prior approval of the department of his or her 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.

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 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.
Master of Science Program in Management Science and Engineering

In collaboration with the Graduate School of Business’ 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 the Graduate School of Business’ 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.)

DOCTORAL DEGREES: ENG.SC.D. AND PH.D.

Two doctoral degrees in engineering are offered by the University: the Doctor of Engineering Sciences, 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 may 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 his or her 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 show, 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 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 doctoral course E9800: Doctoral research instruction (see below). The candidate for the degree of Doctor of Engineering Science must submit evidence that he or she has been admitted to candidacy in compliance with requirements set by the Faculty of Engineering and Applied Sciences.

Doctoral Research Instruction

An Eng.Sc.D. candidate is required to complete 12 credits in the doctoral 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 requirement, e.g., 30 points beyond the master’s degree or 60 points beyond the bachelor’s degree. 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.
4. A student must register continuously throughout 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 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 Columbia Video Network without leaving their work sites. 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...
ENGINEERING 2020–2021

COLUMBIA VIDEO NETWORK

Columbia Video Network

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. Over 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

CVN offers part-time online graduate degree, certificate, and non-degree programs. 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, in the Fall and one in the Spring semesters.

Fields of Study:
- Applied Mathematics
- Applied Physics
- Biomedical Engineering
- Chemical Engineering
- Civil Engineering
- Civil Engineering: Construction Engineering and Management
- 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

MS. Application

The M.S. application requires a minimum cumulative undergraduate GPA of 3.0, a resume/CV, a 250-word personal/professional statement, and a $150 application fee. Applications are reviewed on a rolling basis and decisions are issued within a week of submission.

Doctor of Engineering Science (DES) Degree Programs (Hybrid)

The DES requires 30 credits of online courses and a research project that is completed on campus with a faculty advisor. 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. Participants must select their faculty advisors prior to submitting their applications.

Fields of Study:
- Computer Science*
- Earth and Environmental Engineering
- Electrical Engineering
- Mechanical Engineering

*Only available to applicants who have earned an M.S. in Computer Science from Columbia University.

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, and a $150 application fee. Applications are reviewed on a rolling basis and decisions are issued within a week of 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.

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

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 non-degree course, provided that the student has met the prerequisites for that course.

Up to six credits earned as a non-degree student may be applied towards the MS course requirements. Earning credit as a non-degree 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.
Office of Graduate Student Affairs
530 S. W. Mudd, MC 4708
500 West 120th Street
New York, NY 10027
212-854-0438
seagradadm@columbia.edu

gradengineering@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 graduate 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 (IE, LAS/PAI, and AMIDEAST), and by the Danish-American Fulbright Commission (DAF), Deutscher Akademischer Austauschdienst (DAAD), and Viet Nam 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 seagradadm@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 (TOELF), International English Language Testing System (IELTS), 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, 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 fail 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.Sd.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 deadlines: 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 Lamont 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 3.0 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.

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.Sd.D. with approval from the academic department and the Office of Graduate Student Affairs.

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 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.

EXPRESS ADMISSIONS
Students may be admitted in one term only. Applicants may be asked to participate in an interview as part of the application process.
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 his or her own expense, the necessary notebooks, blanks, 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.

Mandatory fees

University service and support fees:
- On-campus full-time master’s programs: $305 fall / $355 spring
- On-campus all other full-time programs: $261 fall / $331 spring
- On-campus part-time master’s programs: $176 fall / $446 spring
- Health and Related Services fee: $610 per term
- International Services charge: $110 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): $300
- Continuing full-time students (12 or more credits): $200
- First-year part-time students (less than 12 credits): $150
- Continuing part-time students (less than 12 credits): $120

All full-time and part-time M.S.-Ph.D. candidates engaged only in research are assessed a Comprehensive Fee of $2,344 per term by The Fu Foundation School of Engineering and Applied Science. Ph.D. candidates engaged only in research are assessed $2,344 per term for Matriculation and Facilities by the Graduate School of Arts and Sciences.

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). The prorated schedule above does not pertain to individual classes 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 Parent Loans
Federal Perkins Loans
Federal PLUS Loans (when disbursed through the University)
Federal Pell Grants
Federal Supplemental Educational Opportunity Grants
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.

Percentage Refund for Withdrawal during First Nine Weeks of Term

For calendars of a different duration, if the entire program is dropped:
- 1st week: 100%
- 2nd week: 100%
- 3rd week: 90%
- 4th week: 80%
- 5th week: 70%
- 6th week: 60%
- 7th week: 50%
- 8th week: 40%
- 9th week and after: 0%
FINANCIAL AID FOR GRADUATE STUDY

FINANCING GRADUATE EDUCATION
The academic departments of Columbia University graduate funds are administered by the Office of Student Financial Planning 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 branch. 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 branch.

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 department. 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 and a living stipend. Duties may include teaching, laboratory supervision, participation in faculty research, and other related activities. Teaching and research assistantships require up to twenty hours of work per week. If you are participating in faculty research that fulfills degree requirements, you may apply for a research assistantship. Assistantships are awarded on the basis of academic merit.

ALTERNATIVE FUNDING SOURCES
External Awards
Because it is not possible to offer full grant and fellowship support to all graduate students and because of the prestige inherent in holding an award through open competition, applicants are encouraged to consider major national and international fellowship opportunities. It is important that prospective graduate students explore every available source of funding for graduate study. In researching outside funding, you may look to faculty advisers, career services offices, deans of students, and offices of financial aid where frequently you may find resource materials, books, and grant applications for a wide variety of funding sources. You must notify both your Columbia Engineering academic department and the Office of Student Financial Planning of any outside awards that you will be receiving.

Funding for International Students
To secure a visa, international students must demonstrate that they have sufficient funds to complete the degree. Many international students obtain support for their educational expenses from family, 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). Spring admissions applicants will not be considered for departmental funding. 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 of 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 204. For more information, please visit www.columbia.edu.

OTHER FINANCIAL AID—FEDERAL AND PRIVATE PROGRAMS
U.S. citizens and permanent residents eligible for 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-aid. 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, enrolled program 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 the VA website 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 a copy 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 determination of your eligibility, contact the Department of Veterans Affairs at 1-888-442-4551. Additional resource information and 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 which authorizes 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 paying tuition and fees from the VA. This school will not:
• Prevent nor 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 Center for Career Education maintains an extensive listing of student employment opportunities. The Center for Career Education (CCE) is located at East Campus, Lower Level, 212-854-5609, careereducation.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 postenrollment 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 off-campus non-need-based employment, contact the Center for Career Education, located at East Campus, Lower Level, 212-854-5609, careereducation.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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<tr>
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<tbody>
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<td><strong>OFFICERS</strong></td>
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<td>Dean</td>
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<td>Andrew Laine, D.Sc.</td>
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<td>Katayun Barmak Vaziri</td>
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<td>Daniel Bauer</td>
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<td>Simon J. L. Billinge</td>
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<td>Associate Professor of Chemical Engineering</td>
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<td>Paul Blaer</td>
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<td>Senior Lecturer in Computer Science</td>
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<td>Professor of Computer Science and of Statistics (Arts and Sciences)</td>
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<tr>
<td>Professor of Applied Physics</td>
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<td>Athanasios Bourtsalas</td>
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<td>Morris A. and Alma Schapira Professor and Professor of Mechanical Engineering</td>
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<td>Adam Cannon</td>
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<td>Senior Lecturer in Machine Learning (Computer Science)</td>
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<td>Kartik Chandran</td>
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<td>Shih-Fu Chang</td>
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<td>The Richard Dicker Professor of Telecommunications (Electrical Engineering) and Professor of Computer Science</td>
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<td>Jingsuang G. Chen</td>
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<td>Thayer Lindsey Professor of Engineering (Chemical Engineering)</td>
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<td>Associate Professor of Biomedical Engineering and of Radiology (Physics)</td>
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<td>Ali Hirsa</td>
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<td>Xiaofan Fred Jiang</td>
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<tr>
<td>Assistant Professor of Electrical Engineering</td>
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</tbody>
</table>
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Dean, Columbia Business School

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Dean, Columbia Business School

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Rene Chevray
Professor Emeritus of Mechanical Engineering

C. K. Chu
F. U. Foundation Professor Emeritus of Applied Physics in the Faculty of Engineering and Applied Science
T
his section contains a descrip-
tion of the curriculum of each
department in the School, along
with information regarding undergradu-
ate 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 cours-
elective courses, and suggestions about
ate and graduate degree requirements,
with information regarding undergradu-
early written at the University.

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each course is preceded by a
is indicated. Included as well are cours-
elective courses, and suggestions about
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with information regarding undergradu-
early written at the University.

### KEY TO COURSE LISTINGS

#### Course Designator
- AHS: Art History
- AMCS: Applied Math and Computer Science
- AMST: American Studies
- APAM: Applied Physics and Applied Math
- APBM: Applied Biomedical Engineering
- APCH: Applied Physics and Chemical Engineering
- APMA: Applied Mathematics
- APPH: Applied Physics
- APC: Architecture
- ASC: Asian Civilization: East Asian
- ASCM: Asian Civilization: Middle East
- AST: Astronomy
- BIOC: Biology and Chemistry
- BOL: Biology
- BIST: Biostatistics
- BMCH: Biomedical and Chemical Engineering
- BME: Biomedical Engineering: Electrical Engineering, and Biology
- BMEE: Biomedical Engineering and Electrical Engineering
- BMEN: Biomedical Engineering
- BMME: Biomedical Engineering and Mechanical Engineering
- BUSB: Business
- CBMP: Computer Science, Biomedical Engineering and Medical Informatics
- CEDOR: Civil Engineering and Operations Research
- CHAP: Chemical Engineering and Applied Physics and Applied Math
- CHBM: Chemical Engineering and Biomedical Engineering
- CHCB: Chemistry, Biology, and Computer Science
- CHEE: Chemical Engineering and Earth and Environmental Engineering
- CHEM: Chemistry
- CHEN: Chemical Engineering
- CIEE: Civil Engineering and Earth and Environmental Engineering
- CIEN: Civil Engineering
- CMIB: Cellular, Molecular, and Biophysical Studies
- CMCS: Computer Science

#### COSA

#### CSBE
- Computer Science and Electrical Engineering

#### CSEN
- Computer Science and English

#### CSOR
- Computer Science and Operations Research

#### DANCE
- Dance

#### DRAIN
- Decision, Risk, and Operations

#### DROM
- Decision, Risk, and Operations Management

#### EACH
- Earth and Environmental Engineering

#### EAE
- Earth and Environmental Engineering and Chemical Engineering

#### EAI
- Earth and Environmental Engineering and International and Public Affairs

#### ECONOM
- Electrical Engineering, Computer Science and Biomedical Engineering

#### ECIE
- Economics and Industrial Engineering

#### ECON
- Economics

#### EEGM
- Electrical Engineering and Biomedical Engineering

#### EECS
- Electrical Engineering and Computer Science

#### EHSC
- Earth and Environmental Sciences

#### EHS
- Earth and Environmental Engineering and History

#### EMME
- Engineering Mechanics and Mechanical Engineering

#### ENME
- Engineering Mechanics

#### EPSC
- Environmental Policy Studies

#### ENG
- Engineering

#### ENGL
- English

#### ENMG
- Environmental Management

#### FNC
- Finance

#### GRE
- Graduate

#### GRAP
- Graphics

#### HIST
- History

#### HUMA
- Humanities

#### IAP
- Industrial and Applied Physics

#### IEOR
- Industrial Engineering and Operations Research

#### IECF
- Industrial and Electrical Engineering

#### IECS
- Industrial and Electrical Engineering and Computer Science

#### IECS
- International Affairs

#### INTA
- International Affairs

#### MATH
- Mathematics

#### MBMB
- Mechanical and Biomedical Engineering

#### MECE
- Mechanical Engineering

#### MECH
- Mechanical Engineering

#### MECN
- Mechanical Engineering

#### MEEM
- Mechanical Engineering and Engineering Mechanics

#### MEIE
- Mechanical Engineering and Industrial Engineering

#### MSAE
- Materials Science and Engineering

#### MSL
- Materials Science

#### ORCA
- Operations Research, Computer Science and Applied Mathematics

#### PHE
- Physical Education

#### PHYS
- Physics

#### PLAN
- Planning

#### POLS
- Political Science

#### PSIO
- Physiology

#### PSY
- Psychology

#### RELI
- Religion

#### SCNC
- Science

#### SIEO
- Statistics and Industrial Engineering and Operations Research

#### SODI
- Sociology

#### SPAN
- Spanish

#### STAT
- Statistics

#### STCS
- Statistics and Computer Science

#### URBS
- Urban Studies

#### VAR
- Visual Arts

#### HOW COURSES ARE NUMBERED

The course number follows each
designator consists of one or two
capital letters followed by four digits. The capital
indicates the level of the
course, as follows:

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
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<tbody>
<tr>
<td>U</td>
<td>Undergraduate course</td>
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<tr>
<td>UN</td>
<td>Undergraduate, Graduate</td>
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<tr>
<td>GR</td>
<td>Graduate Only</td>
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<tr>
<td>W</td>
<td>Interfaculty course</td>
</tr>
<tr>
<td>A</td>
<td>American Language Program</td>
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<tr>
<td>C</td>
<td>Arts and Sciences</td>
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<td>CC</td>
<td>Columbia College</td>
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<td>UN</td>
<td>Undergraduate</td>
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<tr>
<td>GU</td>
<td>Undergraduate, Graduate</td>
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<td>QR</td>
<td>Graduate Only</td>
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#### DIRECTORY OF CLASSES

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

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

An x following the course number
means that the course meets in the fall
semester; y indicates the spring semester.
The Department of Applied Physics and Applied Mathematics includes undergraduate and graduate studies in the fields of applied physics, applied mathematics, and engineering. The graduate program in applied physics includes plasma physics and fusion research; 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 undergraduate 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. Fundamental plasma physics research is being conducted on (1) equilibrium, stability, and transport in fusion plasmas: high-beta tokamaks, spherical tokamaks, and levitated dipoles; (2) magnetophotonic trap: trapped particle instabilities and stochastic transport; (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 instabilities developed at Columbia University are guiding research on NSTX at the Princeton Plasma Physics Laboratory, on the DIII-D tokamak at General Atomic, and for the design of the next generation burning plasma experiment (TREAT) in theoretical plasma physics research, research is conducted in the theory of plasma equilibrium, stability, active control, and microwave diagnostics of plasma equilibrium, stability, active control, and MW instability, 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 nonneutral, nonneutral magnetic fusion, 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 science, polariton physics of surfaces, laser-induced crystallization, and photon integrated circuits.

Solid-state physics. Research in solid-state physics covers nanotechnology and nanomaterials; 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 Nanoe Initiative (CNI), including applications, grain boundaries and interfaces, nucleation in thin films, molecular electronics, nanostructure analysis, and electronic structure calculations.

Applied mathematics. Current research encompasses analytical and numerical analysis of deterministic and stochastic partial differential equations, large-scale scientific computing, fluid dynamics, dynamical systems and chaos, inverse problems, algorithms for data learning, and applications to various fields of physical and biological sciences. The applications to physical sciences include quantum and condensed-matter physics, materials science, electromagnetics, optics, photonics, and multiphysics. The laboratory’s computing infrastructure supports an active research program in 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, and the applied math group has access to a Beowulf cluster. The Computer Science Department at Columbia University has built an Intel-based 600 core computing cluster that is dedicated to performing first-principles computations of materials. Researchers in the department are additionally using supercomputer facilities at the National Center for Atmospheric Research; the Sandia Supercomputing Center; the National Center for Supercomputing Applications in Berkeley, California; the National Leadership Class Facility at Oak Ridge, Tennessee; various allocations via XSEDE; and...
### APPLIED PHYSICS 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>MATH</strong>&lt;sup&gt;1&lt;/sup&gt;</td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) either semester and ODE (3)</td>
</tr>
<tr>
<td><strong>PHYSICS (three tracks, choose one)</strong></td>
<td>UN1401 (3), UN1601 (3.5), UN2601 (4.5)</td>
<td>UN1402 (3), UN1602 (3.5), UN2602 (4.5)</td>
<td>Lab UN1404 (3)</td>
</tr>
<tr>
<td><strong>CHEMISTRY/ BIOLOGY (choose one course)</strong></td>
<td>CHEM UN1403 (3), or higher or BIOL UN2001 (4) or BIOL UN2005 (4), or higher</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
<td>OCC1010 (3) either semester</td>
<td></td>
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</table>

### APPLIED PHYSICS: 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>APPM E3200 (3)</strong> Mechanics</td>
<td>APPI E3100 (3) Intro to quantum mechanics</td>
<td>APPI E3000 (3) Quantum Physics</td>
<td>Course in second AP area (3)</td>
</tr>
<tr>
<td><strong>MSAE E3111 (3)</strong> Thermodynamics</td>
<td>APPI E3101 (3) Linear algebra</td>
<td>APPI E4100 (3) Applied electromagnetism</td>
<td>APPI E4108 (2) Laboratory</td>
</tr>
<tr>
<td><strong>APPH E4010 (3)</strong> Partial differential equations</td>
<td>APPH E4011 (1) Seminar</td>
<td>APPI E4012 (3) Physical optics</td>
<td></td>
</tr>
</tbody>
</table>

### TECH ELECTIVES (3 points)

<table>
<thead>
<tr>
<th>COURSES</th>
<th>TOTAL POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 points</td>
<td>16</td>
</tr>
<tr>
<td>3 points</td>
<td>15</td>
</tr>
<tr>
<td>3 points</td>
<td>16</td>
</tr>
<tr>
<td>3 points</td>
<td>17</td>
</tr>
</tbody>
</table>

<sup>1</sup> They must include at least 2 points of laboratory courses. If PHYS UN2001 is taken as part of the first two years of the program, these technical electives need not include laboratory courses. Technical electives must be at the 3000 level or above unless prior approval is obtained.

### Nontechnical Requirement

<table>
<thead>
<tr>
<th>COURSES</th>
<th>TOTAL POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 points</td>
<td>16</td>
</tr>
<tr>
<td>2 points</td>
<td>15</td>
</tr>
<tr>
<td>3 points</td>
<td>16</td>
</tr>
<tr>
<td>9 points</td>
<td>17</td>
</tr>
</tbody>
</table>

<sup>2</sup> Students take APMA E2101 prior to declaring their major in applied physics. They may use this course to satisfy their ODE requirement with the permission of the faculty adviser.

<sup>3</sup> Undergraduate students the skills, experience, and preparation necessary for several career options, including opportunities to major 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 engineering, or been employed in various technical or financial areas immediately after receiving the B.S. degree.

<sup>4</sup> Opportunities for undergraduate research exist in the many research programs in applied physics. These include fluid and plasma physics, optical and laser physics, and condensed matter physics. Undergraduate students can receive course credit for research or gain access to a faculty member 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 types of application of applied physics (AP) by a course in each of two areas. Approved areas and courses are

### DYNAMICAL SYSTEMS:

- APPI E4100
- APPI E4103

### NUCLEAR SCIENCE:

- APPI E4100

### PLASMA PHYSICS:

- APPI E4101

### PHYSICS OF FLUIDS:

- APPI E4200

### SOLID STATE/CONDENSED MATTER PHYSICS:

- PHYS GU4018

> **BIOLOGICAL MODELLING:** APPI E4400

In addition to these courses, courses listed in the Specialty Areas in Applied Physics can be used to satisfy this requirement with prior approval 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 APPI E4018.
### Applied Mathematics 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>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4)</td>
<td>either semester and ODE (3)*</td>
</tr>
</tbody>
</table>

### Physics (three tracks, choose one)

<table>
<thead>
<tr>
<th>UN1401 (2)</th>
<th>UN1402 (2)</th>
<th>UN1403 (2)</th>
<th>Lab UN1404 (2)</th>
</tr>
</thead>
</table>

### Chemistry/Biology (choose one course)

<table>
<thead>
<tr>
<th>CHEM UN1403 (3), or higher</th>
<th>or BIOL UN2001 (4), or higher</th>
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</table>

### University Writing

<table>
<thead>
<tr>
<th>CC1010 (3)</th>
<th>either semester</th>
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</table>

### Required Nontechnical Electives

<table>
<thead>
<tr>
<th>HUMA CC1001, COCI CC101, or Global Core (3–4)</th>
<th>HUMA CC1002, COCI CC102, or Global Core (3–4)</th>
<th>ECON UN1105 (4) and UN1155 recitation (4)</th>
</tr>
</thead>
</table>

### Required Tech Electives

(3) Student’s choice

### Computer Science

<table>
<thead>
<tr>
<th>ENGI E1108 (3)</th>
<th>any semester</th>
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</table>

### Physical Education

<table>
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<tr>
<th>UN1001 (1)</th>
<th>UN1002 (1)</th>
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</table>

### The Art of Engineering

<table>
<thead>
<tr>
<th>E1102 (4)</th>
<th>either semester</th>
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</thead>
</table>

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1. With the permission of the faculty adviser, students with advanced standing may start the calculus sequence at a higher level.

2. Applied mathematics majors should satisfy their ODE requirement with the Mathematics Department (ordinarily MATH UN2030). Students who take APMA E2101 with the permission of the faculty adviser, students with advanced standing may use this course to satisfy their ODE requirement with the permission of the faculty adviser.

3. These courses are intended primarily as an opportunity to complete the absolutely mandatory first 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.

4. 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.

5. APMA E4903 (taking one in the junior year) and in one in the senior year, due to timing conflicts, but not the junior seminars, APMA E4901 and APMA E4902.

6. 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. Extra 15 points should be technical electives appropriate for one or both majors.

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### Specialties 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 an "A."

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### 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.
  - APHY E4010x: Intro to nuclear science
  - PHYS GU4102x: Intro to atomic physics
  - APMA E4102x: Intro to dynamical systems
  - APMA E4110x: Modern optics
  - APMA E4112x: Laser physics
  - APMA E4200x: Physics of fluids
  - APMA E4205x: 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 the Earth’s climate to earthquakes 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.

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### Required Courses

- APMA E3101 (3) Linear algebra (Applied math, I)
- APMA E4204 (3) Complex variables and ordinary differential equations
- APMA E4203 (3) Introduction to numerical methods (Computational math, I)
- APMA E4901 (3) Seminar

### Application of Physics

- Courses designated MATH, APMA, or STAT (3)
• Basic Physics and Astrophysics

Fundamental physics and astrophysics can be emphasized. Not only is physics providing a deeper understanding of the universe, but it is also testing the fundamental principles of physics.

PHYS UN3002: From quarks to the cosmos: applications of modern physics
ASTR UN3061: General relativity, black holes, and cosmology (J)

• Astrophysics

APMA E4101x: Intro to dynamical systems

• Business and Finance

The knowledge of physics and mathematics is gained in the applied sciences. The program of study leading to the Certification of Professional Achievement in Medical Physics requires, Ph.D. candidates are strongly encouraged to complete ENG 60001–60024 and should consult their program for additional requirements. Ethics training is required of all students pursuing a doctoral degree.

M.S. Program in Applied Physics

The program of study leading to the degree of Master of Science, while emphasizing continuing work in basic physics, permits many options in several applied physics specialities. The program may be considered simply as additional education in areas beyond the bachelor’s degree, 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 director. At least 30 points of the six core courses listed below. The core courses provide a student with a solid foundation in the fundamentals of applied physics, and with the approval of the faculty advisor; other graduate-level courses, with APMA designators not listed below may also count as core courses.

APPH E4300: Modern optics
APPH E4301: Laser physics
APPH E4302: Particle Physics (J)

• Students must take 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 may be applied toward the elective requirements, subject to the approval of the faculty advisor.

Course offerings from the Department of Economics, School of Business, School of International and Public Affairs, or quantitative courses offered by the School of Engineering and Applied Sciences may not be counted as electives toward the degree. Computer science elective courses include:

CSOR W4231: Analysis of algorithms, I
CSOR W4232: Intro to computational complexity
CSOR W4241: Numerical algorithms and arithmetic
CSOR W4252: Computational learning theory

Industrial engineering/operations research elective courses include:

IEOR E4603: Industrial economics
IEOR E4604: Intro to operations research

IEOR E4605: Optimization: models and methods

IEOR E4616: Stochastic models

IEOR E4639: Intro to probability and statistics
IEOR E4640: Advanced engineering and corporate economics
IEOR E4647: Game theoretic models of microeconomics

STAT GU4606: Elementary stochastic processes

*Students must also take a required Research Seminar course, APMA E6101x or y

M.S. Program in Materials Science and Engineering

This program is designed 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 UN3008: Differential geometry
APMA E4191x: Intro to dynamical systems

• Quantitative Biology

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

RECOMMENDED:
BIOL UN2003a–UN2006y: (Intro biology and I)
APPM E4406y: Physics of the human body

OTHER TECHNICAL ELECTIVES (A COURSE IN AT LEAST TWO AREAS RECOMMENDED):

BIOLOGICAL MATERIALS
BIOL GU4073y: The biology and physics of single molecules
CHEN E6450y: Biophysics

BIOMECHANICS
BMEN E3325y: Fluid biomechanics (J)
BMEN E4330y: Solid biomechanics (J)

GENOMICS AND BIOINFORMATICS
BIOL UN3067y: Whole genome bioinformatics (J)
ECEB E4650x: Intro to genomics, molecular biology, and computational biology

CBMB W4761y: Computational genomics

NEUROBIOLOGY
BMUN UN3004y: Neurobiology (J)
BMUN UN3005y: Neurobiology (J)
ELEN E4011x: Computational neuroscience

The second term of biology will be considered a technical elective if a student has credits from at least two other of the recomended courses in quantitative biology at the 3000 level or above.

• Scientific Computing and Computer Science

Advanced computation has become a basic 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 computational science are distributed across the following courses:

MATH UN3006x: Number theory and cryptography
CS W3137x,y: Advanced programming (J)
CS W3203x: Discrete mathematics: intro to combinatronics and graph theory

• 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 foundation for a career in this area are:

PHYS UN3003: Electronics laboratory (J)
MSE A1130x: Introduction to materials science

ELEN E3106x: Solid-state devices and circuits (J)
MSE A1400x: Crystallography
PHYS GU4190y: Solid-state physics
MSE A2620x: Electromagnetic 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 Graduate Committee, 2006, no appointments to graduate students. The core courses provide a student with a fundamental understanding of applied mathematics and contribute 15 points of graduate credit toward the degree. Students must complete five of the following nine courses:

APMA E4101: Principles of applied mathematics
APMA E4102: Intro to dynamical systems
APMA E4103: Applied functional analysis
APMA E4200: Partial differential equations
APMA E4204: Functions of a complex variable
APMA E4205: Intro to numerical methods
APMA E4206: Applied functional analysis
APMA E4301: Intro to partial differential equations
APMA E4302: Numerical analysis for partial differential equations

Students also must take a required Research Seminar course, APMA E6101x 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 may be applied toward the elective requirements, subject to the approval of the faculty advisor.

Course offerings from the Department of Economics, School of Business, School of International and Public Affairs, or quantitative courses offered by the School of Engineering and Applied Sciences may not be counted as electives toward the degree. Computer science elective courses include:

CSOR W4231: Analysis of algorithms, I
CSOR W4232: Intro to computational complexity
CSOR W4241: Numerical algorithms and arithmetic
CSOR W4252: Computational learning theory

Industrial engineering/operations research elective courses include:

IEOR E4603: Industrial economics
IEOR E4604: Intro to operations research

IEOR E4605: Optimization: models and methods

IEOR E4616: Stochastic models

IEOR E4639: Intro to probability and statistics
IEOR E4640: Advanced engineering and corporate economics
IEOR E4647: Game theoretic models of microeconomics

STAT GU4606: Elementary stochastic processes

*Students must also take a required Research Seminar course, APMA E6101x or y

M.S. Program in Materials Science and Engineering

See page 181.

M.S. Program in Medical Physics

This CNPPEF-approved 36-point program in medical physics is designed for the M.S. degree. It is administered by the faculty from the School of Engineering and Applied Science in collaboration with the 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 program 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, E4500, E4500, E4500, E4500, E4500, E4500, E4500. Additional electives include APPH E4711, APPH E6600, APAM E6600, and a third practicum. Up to 6 points of this 36-point program may be waived based on prior equivalent academic work. Students who enter the 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, 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 textbook and lecture notes, consultation with instructors, and/or written or oral examination administered by Program faculty. Students who are not certified by the American Board of Radiology. The examination, on successful completion of the course, is required for graduation. This examination, on successful completion of the course, is required for graduation. This examination, on successful completion of the course, is required for graduation. This examination, on successful completion of the course, is required for graduation. This examination, on successful completion of the course, is required for graduation. This examination, on successful completion of the course, is required for graduation. This examination, on successful completion of the course, is required for graduation.

Certification of Professional Achievement in Medical Physics

This graduate program of instruction leads to the Certification of Professional Achievement in Medical Physics and requires satisfactory completion of six of the following courses:
APPH E4100: Radiation biology
APPH E4101: Medical physics
APPH E4102: Doseimetry
APPH E4103: Anatomy for physicians and engineers
APPH E4104: Applied electrophysiology or APPH E6330: Diagnostic radiology physics
APPH E4105: Dosimetry for civil engineers or APPH E3316: Advanced topics in radiation therapy

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

PH.D. AND ENG.S.C.D. PROGRAMS

After completing the M.S. program, doctoral students specialize in one or more of their programs. Some specializations have specific core requirements for the doctorate; elective courses are determined in consultation with the major advisor. The requirements 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 models and techniques used in various fields of science and engineering. Historically, mathematics has been a tool for describing and understanding natural phenomena. Today, it is developed into a main tool for physics, other sciences, engineering, and technology. It is now becoming important in the biological, geological, ecological, and economic sciences. With the concrete result 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 concerned in problems coming from other fields. Compared with the engineer and the physicist, the applied mathematician is more concerned with the results of practical consequences and the nature of solutions. Compared with the computer scientist, the applied mathematician is more concerned with the accuracy of approximations and the representation of results. No doubt, 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 Sciences specialty includes research on the dynamics of the atmosphere and the ocean; climate modeling; cloud physics; radiation transfer, remote sensing; geophysical/geological fluid dynamics; and geochemistry.

Applied Physics

This doctoral program has three specialties. APPH E4101 Applied physics laboratory is structured for each of the three specialties in the first year of the doctoral program, in addition to the shared basic courses required of each specialty.

Phasimics

This graduate specialty is designed to emphasize preparation for professional careers in plant pathology, 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 core requirements at Columbia University Plasma Physics Laboratory. Specific course requirements for the Phasimics specializations are set with the academic adviser, in consultation with the Committee on Materials Science and Engineering/Solid-State Science and Engineering.

APPH E4102 Advanced topics in quantum mechanics

3 pts. Lect. Professor Herman. This course analyzes the quantummechanical behavior of particles and fields. It uses the Schrödinger equation, solutions for one-dimensional problems, including simple wells, barriers, and the harmonic oscillator. Introduction to the hydrogen atom, atomic physics and X-rays, electron spin.

APPH E4103 Quantum mechanics: fundamentals and applications

3 pts. Lect. Professor Jastrow. Introduction to quantum mechanics. Wave mechanics, matrix mechanics, Schrödinger equation, solutions for one-dimensional problems, and applications to energy spectra and wave functions.

APPH E4105 Applied electromagnetism

3 pts. Lect. Professor Nakarmick. Applications of electromagnetic theory, electric and magnetic fields, Laplace’s equation, multiple expansions, electric field in matter: dielectrics, magnetism, optical properties of matter, and superconductors. Applications of electromagnetism to problems in medicine and other branches of radiation science.

APPH E4106 Physics of the human body

3 pts. Lect. Prof. A. 2021-2022: Professor Herman. Prerequisites: PHYS UN2110 or PHYS UN2112 or PHYS UN2110 or PHYS UN2112 or PHYS UN2110 or PHYS UN2112 and Calculus. This introductory course analyzes the human body from the basic principles of physics. Topics covered include the action of the body, the mechanics of muscle, fluid dynamics of the heart and circulation, vibrations in speaking and hearing, muscle mechanics and electrical excitations in the lungs, vision, structural properties and limits of the eye, and the development and sensing of magnetic fields, and basics of equilibrium and regulatory control. In each case, a simple model of the body’s organ, property, or function will be constructed. This course does not assume a knowledge of general biology, but it is recommended that students have some background in biology. It is intended for physics majors interested in health professions and those with an interest in the basic principles of living systems. The course is structured to provide a common foundation for using the basic principles of physics to understand the workings of the human body, as well as to prepare students for careers in the medical field.

APPH E4100 Advanced topics in radiological physics

3 pts. Lect. Professor Jiang. Prerequisites: PHYS E4103 or PHYS E4101 or equivalent. This course analyzes the human body from the basic principles of physics. Topics covered include the action of the body, the mechanics of muscle, fluid dynamics of the heart and circulation, vibrations in speaking and hearing, muscle mechanics and electrical excitations in the lungs, vision, structural properties and limits of the eye, and the development and sensing of magnetic fields, and basics of equilibrium and regulatory control. In each case, a simple model of the body’s organ, property, or function will be constructed. This course does not assume a knowledge of general biology, but it is recommended that students have some background in biology. It is intended for physics majors interested in health professions and those with an interest in the basic principles of living systems. The course is structured to provide a common foundation for using the basic principles of physics to understand the workings of the human body, as well as to prepare students for careers in the medical field.

APPH E4102 Advanced topics in quantum mechanics

3 pts. Lect. Professor Herman. This course analyzes the quantummechanical behavior of particles and fields. It uses the Schrödinger equation, solutions for one-dimensional problems, including simple wells, barriers, and the harmonic oscillator. Introduction to the hydrogen atom, atomic physics and X-rays, electron spin.

APPH E4103 Quantum mechanics: fundamentals and applications

3 pts. Lect. Professor Jastrow. Introduction to quantum mechanics. Wave mechanics, matrix mechanics, Schrödinger equation, solutions for one-dimensional problems, and applications to energy spectra and wave functions.

APPH E4105 Applied electromagnetism

3 pts. Lect. Professor Nakarmick. Applications of electromagnetic theory, electric and magnetic fields, Laplace’s equation, multiple expansions, electric field in matter: dielectrics, magnetism, optical properties of matter, and superconductors. Applications of electromagnetism to problems in medicine and other branches of radiation science.

APPH E4106 Physics of the human body

3 pts. Lect. Prof. A. 2021-2022: Professor Herman. Prerequisites: PHYS UN2110 or PHYS UN2112 or PHYS UN2110 or PHYS UN2112 or PHYS UN2110 or PHYS UN2112 and Calculus. This introductory course analyzes the human body from the basic principles of physics. Topics covered include the action of the body, the mechanics of muscle, fluid dynamics of the heart and circulation, vibrations in speaking and hearing, muscle mechanics and electrical excitations in the lungs, vision, structural properties and limits of the eye, and the development and sensing of magnetic fields, and basics of equilibrium and regulatory control. In each case, a simple model of the body’s organ, property, or function will be constructed. This course does not assume a knowledge of general biology, but it is recommended that students have some background in biology. It is intended for physics majors interested in health professions and those with an interest in the basic principles of living systems. The course is structured to provide a common foundation for using the basic principles of physics to understand the workings of the human body, as well as to prepare students for careers in the medical field.

APPH E4100 Advanced topics in radiological physics

3 pts. Lect. Professor Jiang. Prerequisites: PHYS E4103 or PHYS E4101 or equivalent. This course analyzes the human body from the basic principles of physics. Topics covered include the action of the body, the mechanics of muscle, fluid dynamics of the heart and circulation, vibrations in speaking and hearing, muscle mechanics and electrical excitations in the lungs, vision, structural properties and limits of the eye, and the development and sensing of magnetic fields, and basics of equilibrium and regulatory control. In each case, a simple model of the body’s organ, property, or function will be constructed. This course does not assume a knowledge of general biology, but it is recommended that students have some background in biology. It is intended for physics majors interested in health professions and those with an interest in the basic principles of living systems. The course is structured to provide a common foundation for using the basic principles of physics to understand the workings of the human body, as well as to prepare students for careers in the medical field.

APPH E430x Physics of solar energy 3 pts. Lect: 3. Professor Chen. General Physics (PHYS UN1403 or UN1402) or mathematics, including ordinary differential equations (such as MATH UN1202 or UN2031) or instructor’s permission. The physics of solar energy including solar radiation, thermodynamics, amorphous and crystalline photovoltaics, thermodynamics of solar energy, physics of solar cells, energy storage and transmission, and physics and economics in the solar era.


APPH E420x Seminar: problems in applied physics 2 pts. Tp: 1. Professor Mauel. 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. Formal presentation of a term paper.

APPH E450x and Special topics in applied physics 1–5 pts. Lect: 5. Professor Gao.

APPH E450x Fundamentals of radiophysics and radiation dosimetry 3 pts. Lect: 3. Professor Mix. Basic physics of internal exposure (radiative decay, production of the characteristic of the different types of radiation (photon, charged and uncharged particles) and mechanisms of their interactions with matter. Essentials of the determination, by measurement and calculation, of absorbed doses from ionizing radiation sources used in medical physics (clinical situations) and for high physics purposes.


APPH E450x Radiobiology for medical physicists 3 pts. Lect: 3. Professor Zeller. Prerequisite: APPH E450x or equivalent or Corquisite: APPH E410x. Interface between clinical practice and quantitative radiobiology. Microdosimetry, dose-rates effects and biological effectiveness threat; radiation biology data, radiation action at the cellular and tissue level; radiation effects on human, animals, carcinogenesis, genetics, genetic radiation protection; tumor control, normal- tissue complication probabilities; treatment plan optimization.

APPH E471x or Radiation instrumentation and measurement, I 3 pts. Lect: 3. Professor Wentworth. Prerequisite: APPH E3100 or equivalent. Basics of detector technology and radiation counting to complex materials. Computation of efficiencies and measurements and sensors. Detector geometry, theory, numerical methods, basic sets, computing, and running open-source CDF codes. Problem sets and a small project.

APPH E470x Seminar: problems in applied physics 2 pts. Tp: 1. Professor Mauel. 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. Formal presentation of a term paper.

APPH E471x Seminar: problems in applied physics 2 pts. Tp: 1. Professor Mauel. 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. Formal presentation of a term paper.

APPH E410x Radiobiology for medical physicists 3 pts. Lect: 3. Professor Zeller. Prerequisite: APPH E450x or equivalent or Corquisite: APPH E410x. Interface between clinical practice and quantitative radiobiology. Microdosimetry, dose-rates effects and biological effectiveness threat; radiation biology data, radiation action at the cellular and tissue level; radiation effects on human, animals, carcinogenesis, genetics, genetic radiation protection; tumor control, normal- tissue complication probabilities; treatment plan optimization.

APPH E471x or Radiation instrumentation and measurement, I 3 pts. Professor Wentworth. Prerequisite: APPH E3100 or equivalent. Basics of detector technology and radiation counting to complex materials. Computation of efficiencies and measurements and sensors. Detector geometry, theory, numerical methods, basic sets, computing, and running open-source CDF codes. Problem sets and a small project.

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APPH E471x Seminar: problems in applied physics 2 pts. Tp: 1. Professor Mauel. 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. Formal presentation of a term paper.
Biomolecular engineering is an evolving discipline in engineering that draws on collaboration among engineers, biologists, and scientists to provide interdisciplinary insights into medical and biological problems. The field has developed its own knowledge base and principles that are the foundation for the academic programs offered in the Department of Biomedical Engineering at Columbia. The programs in biomedical engineering at Columbia (B.S., M.S., Ph.D., Eng.S.D., and M.D./Ph.D.) prepare students to apply engineering and applied science knowledge to biology, medicine, and the understanding of living systems and their behavior, and to develop and test biomedical systems and devices. Modern engineering encompasses sophisticated approaches to measurement, data acquisition and analysis, simulation, and systems thinking. 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 compared by counterparts offered in 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 sciences departments within the Graduate School of Arts and Sciences. The availability of these courses in a university that contains a large teaching hospital and a large teaching 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 designed to prepare advanced research and biological fundamentals. From this basis, the program branch into concentrations of contemporary biomedical engineering fields. The intrinsic breadth of these concentrations is complemented by a substantial elective content, so that complete bachelor's and master's students to commerce professionals in any area of biomedical engineering or 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 engineering. Graduates of the doctoral program are prepared for engineering research activities at the highest level. Areas of particular interest to Columbia faculty include biomechanics (Professors Atteshian, Guo, Huss, Morrison, Mor, and Nerurkar), cellular and tissue engineering (Professors Danner, Hung, Kam, Leonard, Leong, Liu, Mor, Sia, and Vunjak-Novakovic), biosignals and biomedical imaging (Professors Guo, Hielker, Hillman, Jacobs, Konofagou, Kam, Leonard, Leong, Liu, Sia, and Vunjak-Novakovic), biomaterials and biomedical imaging (Professors Danner, Huss, Kam, Leong, Liu, Sia, and Vunjak-Novakovic), biosignals and biomedical imaging (Professors Guo, Hielker, Hillman, Jacobs, Konofagou, Kam, Leonard, Leong, Liu, Sia, and Vunjak-Novakovic), biosignals and biomedical imaging (Professors Danner, Huss, Kam, Leong, Liu, Sia, and Vunjak-Novakovic), biosignals and biomedical imaging (Professors Danner, Huss, Kam, Leong, Liu, Sia, and Vunjak-Novakovic), and Machine Learning (Professor Lu), the Biomedical Engineering Laboratory (Professor Sajda), the Bone Bioengineering Laboratory (Professor Wang), the Biophotonics and Optical Radiology Laboratory (Professor Hielker), and the Bone Bioengineering Laboratory (Professor Guo), the Cell Engineering Laboratory (Professor Huang), the program for Biomaterial and Interface Tissue Engineering (Professor Lu). The program for Biomaterial and Interface Tissue Engineering is designed to provide broad knowledge and apply complex engineering problems by applying principles of engineering, science, and mathematics. The program for Biomaterial and Interface Tissue Engineering is designed to prepare engineering professionals to work in a range of industries, including medical device industry, engineering consulting, and biotechnology. The program for Biomaterial and Interface Tissue Engineering 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 School of Engineering and in the Department of Biomedical Engineering and Applied Science and those needed to meet the 27-point total of nontechnical electives required for graduation.

First and Second Years

As outlined in this bulletin, in the first and second 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 to take 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 ENG E1006. They must take the two-semester BIOE UN2005 and UN2006: Introduction to Biology I & II in the second year, which gives students a comprehensive overview of modern biology from molecular to organism systems. Students must take BMEN E4101: 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 or 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 primary. Good biomedical engineers must master these techniques. In junior year, all students take the two-semester BMEN E4105: Biomedical Engineering laboratory, I & II (BMEN E3910, E3920). In this two-semester laboratory, engineering students hands-on experience the principles and methods of biomedical engineering experimentation, measurement techniques, quantitative theories of biomedical engineering, data analysis, and independent design and biomedical engineering experiments, in parallel to the Biomedical Engineering I & II and Quantitative Physicians courses. In addition, all students must take BMEN E4110: Biosensors for engineers. In the senior year, students are required to take a two-semester capstone design course, Biomedical Engineering design (BMEN E3810 and E3820), in which students work within a team to tackle an open-ended design project in biomedical engineering. The understanding of these core requirements is to provide our biomedical engineering students with the knowledge and understanding of topics in the field of biomedical engineering.

Parallel to these courses in core courses, students are required to take flexible technical elective courses (21 points) to develop a student’s standing of their chosen interests. A technical elective is defined as a 3000-level or above course taught in SEAS or 3000-level or above course in biology, chemistry, biochemistry, or biotechnology. Exclusions include organic chemistry lecture course (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 current pre-registration students who wish to pursue careers in medicine by satisfying most requirements in the biomedical engineering program or fewer than three additional courses. Some of these additional courses may also be counted as nongenereering technical electives. Please see the course tables for schedules leading to a bachelor’s degree in biomedical engineering. However, as engineering students take required courses during the specific term that they are designated in their two-semester sequence, conflicts may arise if courses are taken out of sequence.

Elective Technical Requirements

Students are required to take at least 40 hours of technical 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 in the first two years of the 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.
   a. All 3000-level or higher courses in the Department of Biomedical Engineering, except BMEN E4105, E4106, E4107, E4108, and BMEN 501 and 501. Additionally, BMEN E4000 501 in fall 2019. (Note that only 3 points of BMEN E3966 may be counted toward technical elective degree requirements.)
   b. All 3000-level or higher courses in the Department of Biomedical Engineering, except BMEN E4107: Creative engineering and entrepreneurship.
   c. All 3000-level or higher courses in the Department of Biomedical Engineering, except ENG E4017: History of telecommunication.

On the basis of the above engineering courses, technical electives, a cross-listed course that is greater than 3000-level and with BMEN as its starting call letters will qualify as a BMEN 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 graduate 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. The following are suggested sample curricula in various interest fields in biomedical engineering program. Students do not necessarily need to take all the courses listed; they may substitute other courses, provided they meet the requirements above.

CELL AND TISSUE ENGINEERING

CHEN UN424: Organic chemistry I (3.5)
CHEN UN444: Organic chemistry II (3.5)
BMCH E4500: Biological transport and rate processes (3)
BMEN E4105: Tissue engineering (3.5)
BMEN E4600: Tissue biomechanics and molecular biology applications (3)
BMEN E4120: Dynamic forces of biomedical systems (4)
BMEN E4550: Micro- and nanotechnology in biomedical engineering (4)

BIOMECHANICS

MECE E3100: Introduction to mechanics of fluids (3)
MECE E3103: Mechanics of solids (4)
MECE E3301: Thermodynamics (3)
BMEN E4150: Artificial organs on an engineering content technical elective, as the course is owned by Biomedical Engineering (and cross listed with Chemical Engineering).

Biological transport and rate processes (3)
BMEN E4500: Biological transport and rate processes (3)
BMEN E4550: Micro- and nanotechnology in biomedical engineering (4)

BIOLOGICAL AND BIOMEDICAL IMAGING

ELEN E310: Signals and systems (3.5)
BMEN E4410: Ultrasound imaging (3.5)
BMEN E4420: Biomedical image processing and modeling (3.5)
ELEN E4110: Digital signal processing (3.5)
BMEN E4510: Medical imaging (3.5)
BMEN E4550: Biophotonics (3.5)

NEURAL ENGINEERING

ELEN E310: Signals and systems (3.5)
BMEN E4410: Bioelectricity and biomagnetic circuits in the brain (3.5)
BMEN E4500: Neural control engineering (3.5)
BMEN E4510: Medical imaging (3.5)
BMEN E4550: Biophotonics (3.5)
BMEN E4410: Digital signal processing (3.5)
BMEN E4510: Medical imaging (3.5)
BIOMEDICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

SEMMESTER I  SEMESTER II  SEMESTER III  SEMESTER IV

MATHEMATICS
MATH UN1102 (3)  APMA E2000 (4) either semester

PHYSICS
UN1401 (4, choose one)  UN1402 (4, 4)  UN1403 (4, 5)  UN1501 (4, 5)

CHEMISTRY
UN1403 (4)  UN1404 (4)  UN1503 (3 or semester 1)  UN1507 (4)

UNIVERSITY WRITING
CC1010 (3) either semester

COMPUTER SCIENCE
ENG11006 (3)  or (semester 1)

PHYSICAL EDUCATION
UN1001 (1)  UN1002 (1)

THE ART OF ENGINEERING
ENG11005 (4)  or in semester 1

NONTECHNICAL REQUIREMENTS
HUMA UN1212 (3) or UN1233 (5)

HUMA CCC1001, COCI CCC101, or Global Core (3–4)

ECON UN1105 (4) and UN1155 (4)

TECHNICAL REQUIREMENTS
ELEN E1201 Intro. to EE (3.5)  APMA E2101 (3)  Intro. to applied math
BOL UN2005 Intro. to Biology (4)  BIOL UN3006 (4)  Intro to Biology, 2

TOTAL POINTS
20 19 14.5 15

1 Students can mix these requirements according to what is available.

2 Students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. PhD. candidates are strongly encouraged to complete ENGI E6001–E6004 and should consult their program for PDL requirements.

• Biomechanics: One year of biology and/or physiology, solid mechanics, statics and dynamics, fluid mechanics, ordinary differential equations.

• Cell and Tissues: One year of biology and/physiology, one year of organic chemistry or biochemistry with laboratory, fluid mechanics, ordinary differential equations.

• Biosignals and Biomedical Imaging: One year of biology and/or physiology and/or biochemistry. Linear algebra, ordinary differential equations, Fourier analysis, digital signal processing. Applicatons lacking some of these courses may be considered for admission with stipulated deficiencies that must be satisfied in addition to the requirements of the degree program. Columbus Engineering does not admit students holding the bachelor’s degree directly to doctoral studies; admission is offered either to the M.S. program or to the M.S. program/doctoral track. The Department of Biomedical Engineering also 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. PhD. candidates are strongly encouraged to complete ENGI E6001–E6004 and should consult their program for PDL requirements.
## CURRICULUM AND EXAM REQUIREMENTS

**Major’s Degree**

In consultation with an appointed faculty adviser, M.S. students should select a program of 30 points of credit, divided as follows:

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<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
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<tr>
<td>BIOMEDICAL ENGINEERING: THIRD YEAR</td>
<td>BIOMEDICAL ENGINEERING: THIRD YEAR</td>
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<td>BMEN E3010</td>
<td>(3) Biomedical eng., I</td>
<td>BMEN E3012</td>
<td>(3) Biomedical eng., II</td>
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<tr>
<td>BMEN E3020</td>
<td>(3) Biomedical eng., II</td>
<td>BMEN E3010</td>
<td>(3) Biomedical eng., III</td>
</tr>
<tr>
<td>BMEE E4001</td>
<td>(3) Quantitative physiology</td>
<td>BMEN E3012</td>
<td>(3) Biomedical eng., IV</td>
</tr>
<tr>
<td>BMEN E4110</td>
<td>(4) Biostat. for engineers</td>
<td>BMEN E3020</td>
<td>(3) Biomedical eng., V</td>
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**REQUIRE COURSES**

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<th>COURSES</th>
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<tr>
<td>BMEN E9100</td>
<td>Master’s research</td>
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**ELECTIVES**

- 5 BIOMEDICAL ENGINEERING: ELECTIVES
- 3 STATISTICS: 3 ELECTIVES
- 3 ELECTIVES
- 3 COURSES IN COMPUTATIONAL MODELING OF PHYSIOLOGICAL SYSTEMS
- 3 BIOMEDICAL ENGINEERING: SEMINAR

**MINIMUM AVERAGE**

Students must achieve a minimum grade-point average of 3.2 without research grades to be required to register for this examination.

## Doctoral Degree

**REQUIREMENTS**

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 E6600), plus at least two graduate mathematics courses. One of these can be a graduate-level biostatistics course. If BMEN E6603 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 biostatistics 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, and prepare for the doctoral qualifying examination and to develop expertise in a clearly identified area of biomedicine.

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 years’ coursework (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 committee consists of the student’s advisor and two BME core faculty members (one semester for M.D./Ph.D. students). The committee may recommend modifications. In general, the student is expected to submit his/her research proposal after five semesters of doctoral studies. In accordance with the regulations of the Graduate School of Arts and Sciences, each student is expected to submit a research proposal to a committee of five faculty, one of whom holds primary appointment in the department. The committee considers the proposal and makes recommendation for publication in a peer-reviewed journal prior to award for any of the degrees.

**Degree Program**

Doctoral students 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 E6600), plus at least two graduate mathematics courses. One of these can be a graduate-level biostatistics course. If BMEN E6603 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 biostatistics 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, and prepare for the doctoral qualifying examination and to develop expertise in a clearly identified area of biomedicine.

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 years’ coursework (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 committee consists of the student’s advisor and two BME core faculty members (one semester for M.D./Ph.D. students). The committee may recommend modifications. In general, the student is expected to submit his/her research proposal after five semesters of doctoral studies. In accordance with the regulations of the Graduate School of Arts and Sciences, each student is expected to submit a research proposal to a committee of five faculty, one of whom holds primary appointment in the department. The committee considers the proposal and makes recommendation for publication in a peer-reviewed journal prior to award for any of the degrees.
COURSES IN BIOMEDICAL ENGINEERING


BMEN E310x Biomedical engineering, I 3 pts. Lect. 3. Professor Varadan. Prerequisites: BMEN E2005, BMEN E2006, or instructor’s permission. Consequenses: BMEN E310x, BMEN E310y. Various courses within the field of biomedical engineering. Foundational knowledge of engineering applied to biological and/or medical problems through modern biological techniques, biomaterials, and cell and tissue engineering.

BMEN E320x Biomedical engineering, II 3 pts. Lect. 3. Professor Lu. Prerequisites: BMEN E310x. Various courses within the field of biomedical engineering. Foundational knowledge of engineering methodology applied to biological and/or medical problems through modern biological techniques, biomaterials, and cell and tissue engineering.

ECBM E38xx Introduction to genomic information systems 3 pts. Lect: 3. Professor Lazar. Prerequisites: BMEN E2003 and one of BMEN E2001 or APMA E2101. The information system paradigm of molecular biology. Representation, organization, structure, function, and manipulation of the biocomplex sequences of nucleic acids and proteins. The role of enzymes and gene regulatory properties and how they are documented, retrieved, and analyzed in databases as well as in bioinformatics and genomic engineering. Recombination and other macromolecular processes that are used in simulation and visualization using simple computer programming. Shares lectures with ECBM E48xx, but the work requirements differ somewhat.

BMEN E381x Biomedical engineering laboratory I 3 pts. Lect. 1. Professor Hess. Prerequisites: BMEN E2005 or BMEN E2006. Various courses within the field of biomedical engineering. Foundational knowledge of engineering methodology applied to biological and/or medical problems through modern biological techniques, biomaterials, and cell and tissue engineering. Biomedical experimental design and hypothesis testing. Statistical analysis of experimental measurements. Analysis of variance, post hoc testing, Fisher’s exact test and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound, characterization of excitable tissues, microfluidics.

BMEN E391tx-EC392x Biomedical engineering design, I and II 2 pts. Lect: 1. Professor Hannon and Apte. Prerequisites: BioE 3001, BiO 4010, and Apte. Biomedical instrument design sequence to be taken in the same year. Elements of the design process, with specific applications to biomedical engineering: process 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 1: statistical analysis of human motion capture data, kinematic analysis, molecular characteristics, analytical, logic, experimental, development of design prototypes, head, approach, benefits and competition analysis. Semester 2: spiral development process and testing, iteration and refinement of the initial design prototypes, and business plan development. A lab fee of $105 each is collected.

BMEN E398xx or x Projects in biomedical engineering 3–6 hrs. To be arranged. Members of the faculty and independent projects involving experimental, theoretical, computational, or engineering design work. May be repeated, but not more than 3 points of this or any other projects or research course may be counted toward the technical degree requirements as engineering technical electives.

BMEN E399xx, or x A Fieldwork 3 pts. Professor Oldham. Prerequisites: Obtained internship and approval from faculty advisor. BMEN undergraduate students only. May be used toward the technical degree requirements only for BMEN undergraduate students who have 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 nontechnical degree requirements. May not be taken for pass/credit or audited.

BMEN E400x or x Special topics 3 pts. Ject.: 3. Members of the Faculty. Prerequisites: Approval of the instructor. Subject matter will vary by year. Instructors may impose prerequisites depending on the topic.

BMEN E401x Quantitative physiology: I cells and molecules 3 pts. Lect.: Professor Kim. Prerequisites: BMEN E2005 or BMEN E2006. Prerequisites: BMEN E310x. Physiological Systems in the cellular and molecular level are examined in a highly quantitative manner. Topics include chemical kinetics, molecular binding and energy, processes, molecular motors, biological membranes and macromolecules.

BMEN E402x Quantitative physiology: II organ systems 3 pts. Lect.: Professor Morrison. Prerequisites: BMEN E401x. BMEN E3200x, BMEN E3205. Consequenses: BMEN E320x, BMEN E3205. Students are introduced to a quantitative approach to analyze and interpret physiological data: analysis of covariance (ANCOVA), logistic regression, multiple linear regression, analysis of variance, post hoc testing. Applied to basic biology and mammalian physiology. Beginning with biological entities related to the cell, the course examines the major physiological systems of the human body (nervous, circulatory, respiratory, renal).

BMEN E401y Ethics for biomedical engineers 3 pts. Lect. 2. Not offered in 2020–2021. Prerequisites: senior status in biomedical engineering and BMEN E401x. Covers a wide range of ethical issues expected to confront biomedical engineers in their careers as researchers, industry, or medical careers. Topics vary and incorporate guest speakers from Physicians and Medical School, Columbia College, and local industry.

BMEN W4020x Computational neuroscience: circuits in the brain 3 pts. Lect. 3. Professor Lazar. Prerequisites: ELEN E3601 or BMEN 3004. Theoretical foundation of synaptic and neuronal activity, the Hodgkin-Huxley neuron, modeling chemical synapses, and communicators in the neuron and the brain; neural mass models for computational neuroscience. Understanding the brain organization and function and neural encoding; stimulus representation with time encoding, encoding of neural circuits with feedback, population time encoding machines. Online lectures: spike micro- processing and neural computing, synaptic plasticity and learning algorithms, unsupervised learning and neural information coding, basic dendritic integration. Projects in MATLAB.

BMEN E407y Computing with brain circuits of model organisms 2 pts. Lect.: Professor Wang. Prerequisites: BMEN E401x or BMEN 3004 and Python. Prerequisites for BMEN 4020. Introduction to behavioral and neural circuit models in model organisms. Prerequisites: ELEN E3601. Prerequisites: BMEN E310x or BMEN E310y. Electrophysiological recording methods, synaptic plasticity and neural computation, synaptic plasticity and learning algorithms, unsupervised learning and neural information coding, basic dendritic integration. Projects in MATLAB.

BMEN E410x Neural control engineering 3 pts. Lect. 2. Professor M. Prerequisites: BMEN E410x. Topics include basic control theory, feedback control systems, the Hodgkin-Huxley model, simple nonlinear models, ion channel models and synaptic models, and the control of muscle contraction. Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, cortico-spinal integrations and spinal circuits estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and thalamic sensory pathway, neural encoding: model: spike triggered average and spike triggered covariance (STC) analysis, neuronal response modulation, and neural adaptation for Parkinson’s disease treatment, motor neural prostheses, and sensory neural prostheses.

BMEN E404yx or y Neural networks and deep learning 2 pts. Lect.: Professor Kostkos. Prerequisites: BMEN E4020 or BMEN E4040x or BMEN E4045 or ELEN E4705 or BMEN 7071. Prerequisites: BMEN E401x or BMEN E401y, or equivalent. Neural networks and deep networks; back propagation in multilayer perceptrons, regression, reinforcement learning, control. Modern models of optimization for training deep models, convolutional neural networks, recurrent and recursive networks, deep learning in speech and object recognition.

BMEN E405y or y Electrophysiology of human memory and navigation 3 pts. Lect.: Professor Jacobs. Prerequisites: Instructor’s permission. Human memory, including working, episodic, and procedural memory. Electrophysiology of cognition, sensorimotor control, and motion. Anatomy of the brain: basis of spatial navigation, with links to spatial and episodic memory. Computational models of memory, brain stimulation, lesion and studies of human navigation.

BMEN E406x Introduction to genetic information 3 pts. Lect.: Professor Anastasios. Prerequisites: None. Introduction to the information system paradigm of molecular biology. The role of enzymes and genes regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Principles of model organisms and their use as a training tool for modern biology, macromolecular behavior in natural cells, and the functional map of the fruit fly. Memory, brain stimulation, lesion studies. Prerequisites: ELEN E3801. Topics include information analysis, computer science, and neural networks. Prerequisites: none. Developing features and information extraction using computer programming.

BMEN E411y Biostatistics for engineers 3 pts. Lect.: Professor Wang. Prerequisites: BMEN E410x or BMEN E410y or BMEN E410z. Prerequisites: BMEN E410x, BMEN E410y, or BMEN E410z. Prerequisites: ELEN E3601 or BMEN 3004 and Python. Probability distributions, hypothesis testing. Fluid shear and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound. Fluid shear and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound. Fluid shear and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound. Fluid shear and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound. Fluid shear and cell adhesion, neuro-electrophysiology, soft tissue biomechanics, biomedical imaging and ultrasound.

BMEN E410y or y Neural networks and deep learning 2 pts. Lect.: Professor Kostkos. Prerequisites: BMEN E4020 or BMEN E4040x or BMEN E4045 or ELEN E4705 or BMEN 7071. Prerequisites: BMEN E401x or BMEN E401y, or equivalent. Neural networks and deep networks; back propagation in multilayer perceptrons, regression, reinforcement learning, control. Modern models of optimization for training deep models, convolutional neural networks, recurrent and recursive networks, deep learning in speech and object recognition.

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BMEN E4320x or y Fluid biomechanics
Prerequisites: APMA E2101, MATH E1301, and CHEM E1301. The course will be accompanied by data analysis assignments using MATLAB.

BMEN E4330y Biomechanics of cells and tissue regeneration
Prerequisites: BMEN E3200 and BMEN E4302 or equivalents. Survey of experiments and theoretical analyses of the mechanical behavior of individual living human cells. Emphasis on understanding the mechanical principles and constitutive relationships for such cells, with an emphasis on the mechanostat function of various tissue properties. Medical and clinical implications of tissue mechanical behavior.

BMEN E4410x Ultrasound in diagnostic imaging
3 pts. Lect. 3. Professor Chhib. Prerequisites: APMA E2101 or APMA E2011 or equivalent. Fourier analysis. Physics of ultrasonic imagery 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 modeling

BMEN E4430y Principles of magnetic resonance imaging
3 pts. Lect. 3. Professor Aluchin. Prerequisites: PHYS UN4043 and APMA E2010, or ELEN E1302, or MATH E1302, or MATH E1303, or MATH E1304, or equivalent. An quantitative analytic description using continuum mechanics and diffusion theory of the magnetic flow from the standpoint of statistical mechanics and mechanical models. Mechanics of erythrocytes, leukocytes, endothelial cells, and fibrinoids; models of aggregation, adhesion, locomotion, amoeba modulus, cell division and morphogenesis; molecular level models of force, motion, microrobots, and intermediate filaments and relation to mechanical properties of cells and cytoplasm. Alternative models of cytoskeletal mechanics, foam theory, tensegrity. Analysis of experimental techniques including micropipette studies, optical and magnetic cytometry, and nanorobiology.

BMEN E4440y Wavefronts in biomedical image and signal processing
3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: APMA E2101 or E2011 or equivalent. An introduction to methods of wavefront analysis and processing techniques for the quantification of biomedical images and signals. Topics include frames and wavelets, reconstruction, multiresolution algorithms for denoising and image restoration, multiresolution feature extraction and classification methods for computer aided diagnosis.

BMEN E4460y Ultrasound in diagnostic imaging

BMEN E4501x Biomaterials
3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: MATH E1030, BMEN E4201, or equivalent. Principles of dental and craniofacial tissue engineering, synthetic and natural polymers and other materials in drug and gene delivery, with focus on recent advances in the fields of biotechnology, biocompatibility, and mechanistic substitutes. Topics include biocompatibility, biological grafts, gene therapy, tissue engineering, and biofilm formation.

BMEN E4520y Synthetic biology: principles of genetic circuits
3 pts. Lect. 3. Professor Danino. Prerequisites: BIOL E1201, MATH U1202, MATH UN1201, and either APMA 3040 or Python R programming, and background in probability, statistics. Recommended: COMS W1717. Introduction to statistical machine learning methods using applications in genomic data and in particular high-dimensional single cell data. Concepts will be mapped to general methods for testing genetic technologies, challenges of high-dimensional data analysis and statistical approaches. Iterative and bootstrap methods. Fit criteria. Wide applicability: medical, energy, others. MATLAB and Simulink environments.

BMEN E4640y Physiological control systems

BMEN E4670y Medical and biological transport and rate processes

BMEN E4680y Dental and craniofacial tissue engineering
3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: MSAE E1303, BMEN E4201, or equivalent. Principles of dental and craniofacial tissue engineering, synthetic and natural polymers and other materials in drug and gene delivery, with focus on recent advances in the fields of biotechnology, biocompatibility, and mechanistic substitutes. Topics include biocompatibility, biological grafts, gene therapy, tissue engineering, and biofilm formation.

BMEN E4700x Science and engineering of body fluids
3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: CHEM E1301, E1302, and PHYS E1501. The course will be accompanied by data analysis assignments using MATLAB.

BMEN E4705y Foundations of nanobiotechnology
3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: BIOL UN2005, UN2106. Students will need proficiency in Python/R programming and understanding of basic principles of nanobiology, scientific foundations, engineering principles, current environmental and policy issues. Applications are discussed of biomolecular and cell engineering, fabrication and control in biomedical systems, and of mimicking as an example of nano-scale factory.

BMEN E4805x Biomimetics: cellular and molecular signaling
3 pts. Lect. 3. Professor Aiazzi. Prerequisites: CHEM UN2440, UN2506, or equivalent. Principles of biological signal propagation and processing. An introduction to the use of signals in cellular and tissue engineering. Applications in cell biology, tissue engineering, and artificial neural networks and recurrent neural networks. Deep autoencoders for dimensioning and segmentation and for translation of cancerous tissue into a biomechanical model of disease. Theory and mechanisms linked to the development of cellular structures from biomedical image analysis including analysis of neurographs of the brain (MRI), CT images of the lung for cancer (CT), cardiovascular ultrasound, Assignment programs will use tensorflow, Pytorch and Jupyter Notebooks. Examinations and a Final Project. Applications and case studies.

BMEN E4900x Tissue engineering
3 pts. Lect. 3. Professor Katz. Prerequisites: BIOL UN2005, BMEN E4200, or BIOL E2005, 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 transitions, and lipid rafts. This course will be led by student presentations and students will read discussions of recent journal articles.

BMEN E5945x Anatomy for physicists and engineers
3 pts. Lect. 3. Professor Katz and Reznikoff Prerequisites: Engineering physics or equivalent. An introduction to human anatomy of the body. A systematistic approach to the study of the human body...
BMEN E4702x Advanced musculoskeletal biology
Advanced analysis and modeling of biological systems, including bones, cartilage, and soft tissues. Selected topics may include biomechanics and tissue remodeling. Prerequisites: BMEN E4701 or equivalent.

BMEN E4704y Biomechanical imaging
Covering image formation, methods of analysis, and digital representation of images. Discussion of modeling approaches using simulation models and applications. Prerequisites: ELEN E1201, COMS W1005.

BMEE E4740y Bioinstrumentation
Learn to design, build, and apply biotransducers in biomedicine. Emphasis on the design phase of the instrument development process. Prerequisites: BMEN E4540y and BMEN E4840y.

BMEN E4840y Functional imaging for the brain
Prerequisites: APMA E2101, APMA E4200, ELEN E8361, or instructor’s permission. Fundamentals of medical functional imaging, including optical, magnetic resonance, positron emission, and single photon imaging. Selected topics to discuss recent literature in brain imaging and neuroengineering. Prerequisite: APMA E2101 or equivalent.

BMEN E4999x and y Graduate fieldwork
1–2 pts. Professor Reuther.
Elements of research design for tissue engineering and regenerative medicine. Real-world experience for graduate students. Elements of research design. Prerequisite: instructor’s permission. Provides a broad-based introduction into the field of Biophotonics. Fundamental concepts of optical, thermal, and chemical interactions with living systems. Tutoring in experimental design and methods of data interpretation. Prerequisites: PHYS UN101 and PHYS UN102.

CBMF W471y Computational genomics
3 pts. Lect. 3. Professor Pe'er.
Working knowledge of one programming language, and some background in probability and statistics. Computational techniques for analyzing and understanding genetic data, including DNA, RNA, protein and gene expression data. Basic concepts in molecular biology relevant for computational analysis of biological data. Emphasis on techniques from computer science, artificial intelligence and machine learning. String matching algorithms, dynamic programming, hidden Markov models, expectation-maximization, neural networks, clustering algorithms, support vector machines. Students will evaluate in class, and present the results of their projects. Prerequisites: ELEN E1201, APMA E2101 or equivalent, or instructor’s permission. Engineering perspective on the study of light-matter interactions. Applications of principles in neuroengineering; neural codes. Stimulus recovery with time decoding models of transduction pathways. Robust adaptation models of sensory processing in neural systems. Implementation strategies. Real-world training in biomedical design and innovation. Prerequisite: 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 6070 to 6077.

EBCM E6060-6069x or y Topics in neuroimaging and neuroengineering
3 pts. Lect. 2. Members of the faculty. Prerequisites: 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 6070 to 6077.

EBCM E6080-6089x or y Topics in computational neuroimaging and neuroscience
3 pts. Lect. 2. Professor Sajda.
Prerequisite: Instructor’s permission. Selected advanced topics in computational neuroimaging and neuroscience. Content varies from year to year, and different topics rotate through the course numbers 6070 to 6077.

BMEN E6001x Current topics in biophysics
4 pts. Lect: 4. Instructor’s permission. Sympathetic nervous system: anisotropic elasticity, viscoelasticity, and integral feedback. Stimulus representation models of transduction pathways. Robust adaptation models of sensory processing in neural systems. Implementation strategies. Real-world training in biomedical design and innovation. Prerequisite: 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 6070 to 6077.

BMEN E6007x Current topics in nanoimaging and neuroengineering
Prerequisites: APMA E2101, APMA E4200, ELEN E8361, or instructor’s permission. Fundamentals of medical functional imaging, including optical, magnetic resonance, positron emission, and single photon imaging. Selected topics to discuss recent literature in brain imaging and neuroengineering. Prerequisite: APMA E2101 or equivalent.

BMEN E6105y Biomedical modeling I
3 pts. Lect. Professor Reuther.
Prerequisites: BMEN E4540y and BMEN E4840y or equivalent, and APMA E4200 or equivalent. Advanced computational modeling and quasilinear partial differential equations. Concepts of biological systems from molecules to organs. Selected systems are analyzed in depth with an emphasis on the underlying principles that govern biological systems. Topics may include cell signaling, molecular transport, excitability membranes, respiratory physiology, nerve transmission, circulatory control, auditory signal processing, muscle physiology, actomyosin modeling, 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 ultrasonic imaging. Fundamentals of digital image analysis. Prerequisite: BMEN E4540y or Y/BME E4408.

BMEN E6201x and y Advanced biomaterials & tissue engineering
3 pts. Lect. 2. Not offered in 2020–2021. Prerequisites: APMA E2101, APMA E4200, ELEN E8361, or instructor’s permission. Fundamentals of medical functional imaging, including optical, magnetic resonance, positron emission, and single photon imaging. Selected topics to discuss recent literature in brain imaging and neuroengineering. Prerequisite: APMA E2101 or equivalent.

BMEN E6205y Advanced functional imaging
Prerequisite: BMEN E4540y. Format methods in computational neuroscience including methods of signal processing, communication theory, information theory, and deterministic and stochastic models of identification and machine learning. Molecular models of transduction pathways. Robust adaptation models of sensory processing in neural systems. Implementation strategies. Real-world training in biomedical design and innovation. Prerequisite: 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 6070 to 6077.

BMEN E6410x Principles and practices of in vivo and in vitro biocompatibility
Prerequisites: BMEN W4020 and APMA E2101 or equivalent, or instructor’s permission. Fundamentals of medical functional imaging, including optical, magnetic resonance, positron emission, and single photon imaging. Selected topics to discuss recent literature in brain imaging and neuroengineering. Prerequisite: APMA E2101 or equivalent.

BMEN E6450y Biomechanical imaging
3 pts. Lect. 3. Professor Reuther.
Prerequisites: BMEN E4540y and BMEN E4840y or equivalent, and APMA E4200 or equivalent. Advanced computational modeling and quasilinear partial differential equations. Concepts of biological systems from molecules to organs. Selected systems are analyzed in depth with an emphasis on the underlying principles that govern biological systems. Topics may include cell signaling, molecular transport, excitability membranes, respiratory physiology, nerve transmission, circulatory control, auditory signal processing, muscle physiology, actomyosin modeling, 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 ultrasonic imaging. Fundamentals of digital image analysis. Prerequisite: BMEN E4540y or Y/BME E4408.

BMEN E6505x or y Advanced biomaterials & tissue engineering
3 pts. Lect. 2. Not offered in 2020–2021. Prerequisites: APMA E2101, APMA E4200, ELEN E8361, or instructor’s permission. Fundamentals of medical functional imaging, including optical, magnetic resonance, positron emission, and single photon imaging. Selected topics to discuss recent literature in brain imaging and neuroengineering. Prerequisite: APMA E2101 or equivalent.
**Chemical Engineering**

801 S. W. Madison, MC 4721
212-854-2965
cheme.columbia.edu

Dr. Christopher Durning

**Chair**

Jingyue Ju,

Professor

**Associate Chair**

Samuel Ruben–Peter Venkatasubramanian,

Professor

**Director of Finance and Administration**

Jingguang Chen,

Professor

**Assistant Chair**

Robert Buzic,

Professor

**Professorial Lecturer**

Aaron Moment

**Adjunct Professors**

Elis Matias,

Kesavan Ravichandran,

Christian Tontos

**Principal Investigators**

Aghavni Bedrossian–Onar,

Kristine Hartings,

Gregory Hounsell

**Research Assistants**

Olga Gang,

Benjamin Durnett

**Associate Professors**

Christopher 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 E9000x** 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 the credit is contingent upon the submission of an acceptable thesis.

**BMEN E9000x** or **y** Doctoral research

1–6 pts. Members of the faculty.

A candidate for the Ph.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 E9000x** or **y** Doctoral dissertation

1–6 pts. Members of the faculty.

A candidate for the doctoral 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.

**BMEN E91000** or **y** Biomedical engineering seminar

2 pts. Sem: 1. Professors Davina, 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 E9000x** or **y** Doctoral research

1–6 pts. Members of the faculty.

A candidate for the Ph.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 E9000x** or **y** Doctoral dissertation

1–6 pts. Members of the faculty.

A candidate for the doctoral 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.
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 Bench-top Moisture Analyzer units, and 15 computer work stations. State-of-the-art specialized research equipment are housed within individual faculty laboratories. Shared research laboratories 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.

CHEMICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

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<tr>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
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<tr>
<td>MATH UN101 (3)</td>
<td>MATH UN102 (3)</td>
<td>APMA E2000 (4) or either semester</td>
<td>MATH elective (3)*</td>
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<td>PHYSICS (three tracks, choose one)</td>
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<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>UN1404 (3)</td>
<td>Lab UN1404 (2)</td>
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<td>UN1001 (3)</td>
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<td>UN1403 (4) and Lab UN1003 (2)</td>
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<td>UN1004 (4) and Lab UN1003 (2)</td>
<td>UN2443 (4)</td>
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CHEMISTRY (three tracks, choose one)

| UN1403 (4) and Lab UN1003 (2) | UN1404 (4) | UN1004 (4) and Lab UN1003 (2) | UN2443 (4) |

UNIVERSITY WRITING

CC1010 (5) or either semester

REQUIRED NONTECHNICAL ELECTIVES

One core humanities elective (3–4 points)* Three core humanities electives (11 points)*

CHEMICAL ENGINEERING PROGRAM: THIRD AND FOURTH YEARS

<table>
<thead>
<tr>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
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<tr>
<td>CHEN E3110 (3)</td>
<td>Transp. phenomena, I</td>
<td>CHEN E3120 (3)</td>
<td>Transp. phenomena, I</td>
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<tr>
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<td>Principles of chem. eng. thermodynamics</td>
<td>CHEN E3220 (3)</td>
<td>Chem. eng. thermodynamics</td>
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<td>CHEN E3340 (3)</td>
<td>Reaction kinetics and reactor design</td>
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<td>PHY E2101 (3)</td>
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<td>ECE E4140 (3)</td>
<td>Eng. separations processes</td>
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REQUIRED COURSES

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<th>REQUIRED LABS</th>
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<td>CHEN UN495 (1.5)</td>
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<td>CHEN UN496 (1.5)</td>
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<td>CHEN E4300 (3)</td>
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<td>CHEN E3810 (3)</td>
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THE ART OF ENGINEERING

ENGI E1006 (3)

TOTAL POINTS*

17 18 16.5 18

CHEMICAL ENGINEERING: THIRD AND FOURTH YEARS

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REQUIRED LABS

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TOTAL POINTS

16.5 16.5 16 15

* Four core humanities electives should be taken as follows: In Semester II, HUMA CC1001 or CC01 CC1101 (4) or any initial course in one of the Global Core sequences in the College (3–4); in Semester IV, HUMA E2100 or CC5201 102 (3) or ASOM UN2002 in the second course in the Global Core sequence elected in Semester II (3–4) also in Semester IV, ECON UN1105 (4) with UN1155 elective (0) and either HUMA UN121 or UN122 (3).

** Should be taken in Semester II, but may be moved upon advisor’s approval to Semester V if CHEM UN2495 is taken in Semester III. This course fulfills the SEAS professional engineering elective requirement.

** Taking the first track in each row and E1102 in Semester II.

** Elective options include APMA E2101, MATH UN1210, APMA E3102, APMA E4001, APMA E4300, STAT GU4001, or another course approved by the major advisor.

** The total of 21 points (7 courses) of required technical electives must include five engineering courses, two of which must be in chemical engineering and one must be outside chemical engineering, and 6 points (2 courses) of “advanced science” (i.e., courses in chemistry, physics, biology, and certain engineering courses, one of which must be outside engineering).

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 experimental, 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.

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 experimental, 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 somewhat similar, there are a few important differences for chemical engineering majors. Those wishing to learn about, or major in, environmental, establish goals, plan tasks, and meet objectives.

Leadership positions in industries that require technical expertise in 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.
chemical engineering should take the professional elective CHEN E2100 Introduction to chemical engineering in their second year of the Chemical Engineering Department. This course is a requirement for the chemical engineering major and serves as a technical elective for other engineering majors. Those wishing to pursue a dual major in Chemical and also take ENGI E0106 introduction to computing for engineering and appropriate courses in the Chemical engineering majors receive additional instruction in their junior year on the use of computational methods to solve chemical engineering problems.

In the junior-senior sequence one specializes in the chemical engineering major. The table on page 7 outlines the core course requirements, which are split between courses electing engineering courses as well as those emphasizing particular 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 also shows that a significant fraction of the junior-senior program is reserved for electives, both technical and non-technical. Non-technical electives are courses that are not significant engineering content (i.e. art, history, languages, and presentation skills, competency with computers). 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. Alternatively, 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 E0900 Undergraduate research 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 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: chem.columbia.edu).

Requirements for a Minor in Chemical Engineering
See page 205.

PROGRAM GRADUATES
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 degrees in other related fields such as physics, chemistry, and biochemistry, the Ph.D. program provides the opportunity to work 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. The graduate candidates are strongly encouraged to complete ENGI E9001-6004 and should consult their PDL requirements.

M.S. Degree
The requirements are (1) the core courses listed below in chemical engineering (CHEN E4010)-General, differential equations (APMA E4020), Transport phenomena, III (CHEN E4110), Advanced chemical kinetics (CHEN E4130), and Advanced chemical engineering thermodynamics (CHEN E4136)-Statistical mechanics (CHAP 4123); and (2) 18 points of 4000-level courses, approved by the graduate coordinator and research advisor, of which up to 6 may be a Master’s research (CHEN 9400). Students with undergraduate preparation in physics, chemistry, biochemistry, pharmacy, and related fields may take advantage of a special master’s social science program to the master’s degree in chemical engineering. This program enables such students to avoid several of the fundamental chemical engineering courses in the bachelor’s degree program. Doctoral Degrees
The Ph.D. and D.E.S. degrees have essentially the same requirements. All students in a doctoral program must complete satisfactory grades in the four core courses (CHEN E4010, E4110, E4330, E4130/CHAP E4120), (2) pass a written comprehensive examination, and (3) propose a dissertation research within 12 months of passing the qualifying exam; (4) defend their thesis; and (5) satisfy residency and course load requirements and the four core courses. For detailed requirements, please consult the departmental graduate 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 E2100 Introduction to chemical engineering 3 pts. Lect. 3. Professor Banta. Prerequisites: 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 chemical and biochemical industries is provided.

CHEN E3010Principles of chemical engineering thermodynamics 3 pts. Emphasis on chemical engineering applications. Prerequisite: CHEM UN1403. Consequences: CHEN E3101. Introduction to thermodynamics. Fundamentals are emphasized; the laws of thermodynamics are derived and their meaning explained and illustrated with applications to engineering problems. Pure systems are treated, followed by an introduction to mixtures and phase equilibrium.


CHEN E3900x Undergraduate research project I 3 pts. Lect. Professor Durning. Prerequisites: CHEN E3202. Developments in Transport I are extended and handled for special topics taken from applications of energy cascades, wall bounded turbulent shear flow, time-averaging of the equations of change, Prandtl's mixing length hypothesis for the Reynolds stress, the Reynolds analogy, continuum modeling of turbulent flows and heat transfer processes, turbulent boundary layers, and turbulence. When the turbulent conditions. Then, macroscopic (system- level) mass, momentum and energy balances for one system components are developed and applied to complex flows and heat exchange processes. The final part focuses on mass transport in mixtures of simple fluids: Molecular level origin of diffusion phenomena, Fick's law and its applications to semiconductor technology and broadline convection mass transport.

CHEN E3910Chemical engineering thermodynamics 3 pts. Lect. 3. Professor Overmay. Prerequisites: CHEN E3010 and CHEN E3101. Consequences: CHEN E3200. Deals with fundamentals and applied thermodynamic principles that form the basis of chemical engineering practice. Topics include phase equilibria, methods to treat ideal and nonideal mixtures, and estimation of properties using computer methods.


CHEN E3151Chemical engineering laboratory 3 pts. Lect. Lab. 3. Professor Av and Bedrossian. Prerequisites: Completion of core chemical engineering curriculum and the approximation of year senior of year (includes: CHEN E3110, E3210, E3210, E3510, E4101, E4103, E4105, CHEN E3102, or instructor's approval.) Emphasizes active, experiment-based resolution of open-ended problems involving use, design, and optimization of equipment, products, or materials. Undergraduate guidance students form faculty, conduct and write up the results of projects, write and present experimental procedures, and present results in oral and written form. Develops skills in analytical, communication, and computer problem solving skills in the context of problems that span from traditional, large scale separations and processing operations to molecular level designs of materials or products. Sample projects include scale up of apparatus, process control, chemical separations, microfluidics, surface engineering, molecular electronics, and alternative energy sources. Satisfaction is integrated throughout the course.

CHEN E4910y Undergraduate research project I 1–6 pts. Members of the faculty. Prerequisites: Instructor's permission and approval from advisor. Restricted to CHEN undergraduate students. Prior work experience in chemical engineering in relevant internship or fellowship experience as part of their program of study as determined in consultation with the academic advisor. A formal research project must be made prior to registration. A written proposal must be submitted for all projects. A written report describing the experience and the role it relates to the chemical engineering core curriculum is required. Employers have the option to assign 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 200 level course. May be repeated for credit, but no more than 15 points of CHEN E4910y may be used for degree credit.

CHEN E400x Essentials of chemical engineering—A 3 pts. Lect. 3. Professor Banta. Prerequisites: 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 sophomore year, including topics from Mass and Energy balance, Process Control, and Transport and the instructor's permission. I and II. Required for all M.S. students with Bachelor to Engineer status, the credits from this course may not be applied toward any chemical engineering degree.

CHEN E400x Essentials of chemical engineering—B 3 pts. Lect. 3. Professor Banta. Prerequisites: 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 sophomore year, including topics from Mass and Energy balance, Process Control, and Transport and the instructor's permission. I and II. Required for all M.S. students with Bachelor to Engineer status, the credits from this course may not be applied toward any chemical engineering degree.

CHEN E4260y Protection of industrial and intellectual property 3 pts. Lect. Professor Spese. To explore the role and function of technology managers to assess 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.

CHEN E4110y Principles of industrial electrochemistry 3 pts. Lect. Not offered in 2020-2021. Prerequisites: CHEN E3110 or E3120 or equivalent. A presentation of the basic principle underlying electrochemical processes. Thermodynamics, electrode kinetics, and ionic mass transport. Examples of industrial and environmental applications are emphasized. Includes: electroplating, electrorefining, and winning in aqueous solutions and in molten salt. Topics include: electrochemical reversibility of chemical equilibria; electron transfer; energy and mass transport; and fuel cells.

APCH E460x Soft condensed matter 3 pts. Lect. Professor Rajagopalan. Prerequisites: MISE E3111, CHEE E3310, or CHEN E3120 or equivalent. Course is aimed at students interested in exploring the physical properties of soft matter and the processes that control them. Introduces fundamental ideas, concepts, and measurements, and applications that depend on and emphasize on biomolecular systems. Covers the broad range of molecular, nanoscopic, and colloidal processes to which their principles can be applied in both physical and biological settings. The relationship between molecular structure and conformation and macroscopic behavior of soft matter is discussed in this course. Experimental methods, including X-ray scattering, neutron scattering, and electron microscopy are reviewed. Example applications illustrated by means of laboratory experiments: elastomers, rubber elasticity, and in atomic and lower dimensional devices. Course grade based on presentations, quizzes, homework assignments, and final project report.

CHEN E4510y Topics in transport phenomena 3 pts. Instructor to be announced. Prerequisites: Undergraduate fluid mechanics, or transport phenomena, or instructor's permission. Self-contained treatments of selected topics in transport phenomena (e.g., mass and momentum transport, chemical reaction, heat transfer). Topics and instructors may change from year to year. Intended for: Under/Upper level undergraduates and graduate students in engineering and the physical sciences.


CHEN E4130x Advanced chemical engineering thermodynamics 3 pts. Lect. Professor O'Shaughnessy. Prerequisite: Successful completion of an undergraduate thermodynamics course. The course provides a rigorous and advanced foundation in chemical thermodynamics. Emphasis is on the principles of chemical reaction thermodynamics. Effects of transport in modifying surface reaction kinetics. Applies basic concepts in the chemical engineering design (transport phenomena, reaction kinetics, thermodynamics, transport) to surface phenomena.


CHEN E4162x Transport phenomena in fluids and mixtures 3 pts. Lect. Professor Durning. Prerequisites: CHEN E3110 and E3120 or equivalent. Develops and applies non-equilibrium thermodynamics for modeling of transport phenomena in fluids and their mixtures. Continuum balances of mass, energy, and momentum for pure fluids; non-equilibrium thermodynamic development of Newton's law of viscosity and Fourier's law; applications (conduction dominated energy transfer, forced and free convection energy transport in fluids); balance laws for fluid mixtures; non-equilibrium thermodynamic development of Full's law; applications (diffusion-reaction problems, analogies between energy and mass transport processes, transport process in electrolyte solutions, sedimentation).

CHEN E4170y Thermodynamics and mathematics of fluids 3 pts. Instructor to be announced. Prerequisites: Undergraduate fluid mechanics, or transport phenomena, or instructor's permission. Self-contained treatments of selected topics in transport phenomena (e.g., mass and momentum transport, chemical reaction, heat transfer). Topics and instructors may change from year to year. Intended for: Under/Upper level undergraduates and graduate students in engineering and the physical sciences.


CHEN E4130x Advanced chemical engineering thermodynamics 3 pts. Lect. Professor O'Shaughnessy. Prerequisite: Successful completion of an undergraduate thermodynamics course. The course provides a rigorous and advanced foundation in chemical thermodynamics. Emphasis is on the principles of chemical reaction thermodynamics. Effects of transport in modifying surface reaction kinetics. Applies basic concepts in the chemical engineering design (transport phenomena, reaction kinetics, thermodynamics, transport) to surface phenomena.


CHEN E4162x Transport phenomena in fluids and mixtures 3 pts. Lect. Professor Durning. Prerequisites: CHEN E3110 and E3120 or equivalent. Develops and applies non-equilibrium thermodynamics for modeling of transport phenomena in fluids and their mixtures. Continuum balances of mass, energy, and momentum for pure fluids; non-equilibrium thermodynamic development of Newton's law of viscosity and Fourier's law; applications (conduction dominated energy transfer, forced and free convection energy transport in fluids); balance laws for fluid mixtures; non-equilibrium thermodynamic development of Full's law; applications (diffusion-reaction problems, analogies between energy and mass transport processes, transport process in electrolyte solutions, sedimentation).

CHEN E4170y Thermodynamics and mathematics of fluids 3 pts. Instructor to be announced. Prerequisites: Undergraduate fluid mechanics, or transport phenomena, or instructor's permission. Self-contained treatments of selected topics in transport phenomena (e.g., mass and momentum transport, chemical reaction, heat transfer). Topics and instructors may change from year to year. Intended for: Under/Upper level undergraduates and graduate students in engineering and the physical sciences.


CHEN E4130x Advanced chemical engineering thermodynamics 3 pts. Lect. Professor O'Shaughnessy. Prerequisite: Successful completion of an undergraduate thermodynamics course. The course provides a rigorous and advanced foundation in chemical thermodynamics. Emphasis is on the principles of chemical reaction thermodynamics. Effects of transport in modifying surface reaction kinetics. Applies basic concepts in the chemical engineering design (transport phenomena, reaction kinetics, thermodynamics, transport) to surface phenomena.
CHEN 9500x y -- S9500 Doctoral research 1–15 pts. Members of the faculty. Prerequisites: The qualifying examinations for the doctoral candidates. 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 9500x y and Advanced Research projects 2–10 pts. Members of the faculty. Prerequisites: Admission to the graduate program by 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 the 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 9500x y and Doctoral research instruction 3. 6 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 9500x may not be used to satisfy the minimum residency requirement for the degree.

CHEN 9500x y and S9500 Doctoral dissertation 1 pt. Members of the faculty. Open only to certified doctoral candidates. A candidate for the doctoral degree 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, and 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. From classical mechanics to the field of applied mechanics, it includes the study of the mechanical and other properties of materials, stress analysis, and the applied mechanics, it includes the study of the mechanical and other properties of materials, stress analysis, and the

Electromechanical systems

Mechanical systems

Moving systems

Vibrations

Electromechanical vibration

Electro-mechanical vibration

Electro-mechanical vibration

Electro-mechanical vibration
engineered systems. Sustainability research is at the hub of the broader sustainability agenda.

Environmental engineering/water resources: modeling of flow and pollutant transport in surface and subsurface systems, study of climate and global change, and habitat development; wind engineering, seismic risk and earthquake control, computational mechanics and multiscale and failure analysis, vibration engineering for composite materials, cable-supported bridges.


Environmental engineering/water resources: modeling of flow and pollutant transport in surface and subsurface systems, study of climate and global change, and habitat development; wind engineering, seismic risk and earthquake control, computational mechanics and multiscale and failure analysis, vibration engineering for composite materials, cable-supported bridges.


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CIVIL 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></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4)</td>
<td>APMA E2101 (5)</td>
</tr>
</tbody>
</table>

**Introduction to Engineering**

- A first course in engineering principles and practices.
- Introduces the design process and problem-solving techniques.
- Emphasizes the role of engineers in society.

**Engineering Mechanics**

- Focuses on the analysis and design of structures.

**Computer Science**

- Introduction to computer science fundamentals.
- Programming concepts and problem-solving techniques.

**Physics**

- Classical mechanics, electromagnetism, and quantum mechanics.
- Covers the behavior of matter and energy.

**Chemistry**

- General chemistry principles.
- Focuses on the composition, properties, and reactions of substances.

**Non-Technical Electives**

- Options to balance academic and personal development.
- Promotes a well-rounded education.

**Total Points**

- Semester I: 3 points
- Semester II: 3 points
- Semester III: 9 points

**Total Credits**

- 11 points

CIVIL 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>
</thead>
<tbody>
<tr>
<td><strong>Core Required Courses</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIEN E3125 (6)</td>
<td>CIEN E3126 (6)</td>
<td>CIEN E3127 (3)</td>
<td>CIEN E3128 (3)</td>
</tr>
</tbody>
</table>

**Civil Engineering**

- Focuses on urban planning, environmental impact assessment, and sustainable development.
- Emphasizes the role of civil engineers in shaping the built environment.

**Geotechnical Engineering**

- Specializes in the behavior of soil and rock masses.
- Covers topics such as soil mechanics and foundation engineering.

**Civil Engineering Concentrations**

- Three concentrations offered:
  - Water systems
  - Structural engineering
  - Construction management

**Civil Engineering Electives**

- 6 points

**Civil Engineering Concentration Electives**

- 3 points

**Total Points**

- 13 points

**Total Credits**

- 18 points

**Summary**

1. An ability to perform engineering analysis and design.
2. An ability to communicate effectively with a range of audiences.
3. 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.
4. 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.
5. An ability to communicate effectively with a range of audiences.
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 include courses in mathematics, physics, and chemistry. The student has a strong foundation in these areas, enabling effective engineering analysis and design.

**Civil Engineering**

The prerequisites for this program include courses in mathematics, physics, and chemistry. The student has a strong foundation in these areas, enabling effective engineering analysis and design.
### ENG Museum Mechanics 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>Mathematics</td>
<td>Math UN1101 (3)</td>
<td>Math UN1102 (3)</td>
<td>APMA E2000 (4)</td>
</tr>
<tr>
<td>Physics</td>
<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>Lab UN1404 (3)</td>
</tr>
<tr>
<td>CHEMISTRY</td>
<td>one-semester lecture (3–4); UN1403 or UN1404 or UN1504</td>
<td>Chem lab UN1500 (3) either semester or physics lab</td>
<td></td>
</tr>
<tr>
<td>MECHANICS</td>
<td>ENME-MECE E3105 (4) any semester</td>
<td></td>
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</tr>
<tr>
<td>UNIVERSITY WRITING</td>
<td>CC1010 (5) either semester</td>
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<td></td>
</tr>
<tr>
<td>REQUIRED NONTECHNICAL ELECTIVES</td>
<td>HUMA CC1001, CC1011, or Global Core (3–4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REQUIRED TECH ELECTIVES</td>
<td>(3) Student’s choice, see list of first- and second-year technical electives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMPUTER SCIENCE</td>
<td>Computer Language: ENGL E1006 (3) or equivalent (any semester)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHYSICAL EDUCATION</td>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
<td></td>
</tr>
<tr>
<td>THE ART OF ENGINEERING</td>
<td>ENGL E1102 (4) every semester</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 concentrations in Construction Engineering and Management, Engineering Mechanics, Environmental Engineering and Water Resources, Forensic (Structural) Engineering, Geotechnical Engineering, and Structural Engineering, or combinations of these areas. There are no required courses at the M.S. level. Every student is assigned a faculty member as an academic advisor. Student and advisor 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 advisor 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. The Master of Science concentrations are:
COURSES IN CIVIL ENGINEERING
See also Courses in Engineering Mechanics at the end of this section.

COURSES IN CIVIL ENGINEERING
See also Courses in Engineering Mechanics at the end of this section.

MECHANICS at the end of this section.

COURSES IN CIVIL ENGINEERING
See also Courses in Engineering Mechanics at the end of this section.

MECHANICS at the end of this section.

COURSES IN CIVIL ENGINEERING
See also Courses in Engineering Mechanics at the end of this section.

MECHANICS at the end of this section.
Prerequisite: CIEN E4243 or equivalent. Seismicity, earthquake intensity, propagation of seismic waves, design of earthquake motion, seismic site evaluation of structural defects and failures of foundations and structural systems, design project and team challenges and responsibilities. Students are required to prepare written reports and make oral presentations of selected cases.  

CIEN E4245x Multihazard design of structures  
3 pts. Lects: Professors Daddario and A. Mossavar-Rahmani.  
Prerequisite: CIEN E3141 or E4242 or instructor’s permission. Fundamental considerations of seismic mechanics; design philosophies; reliability and risk concepts; basics of fluid mechanics; design of structures subjected to blast; elements of spatial seismic design; elements of this design process to overcome the challenges inherent in major projects. Topics include overview of major projects, project context with architecture, design of foundations and structural systems, design project and team challenges and responsibilities. Students are required to prepare written reports and make oral presentations of selected cases.

CIEN E4242x Design of prestressed concrete structures  
3 pts. Lect: 3. Professor Tomasetti.  
Prerequisite: CIEN E4242 or instructor’s permission.  
CIEN E4242x is an introduction to the design of prestressed concrete. Major topics include: methods for the analysis of loads and structural design approaches. Material considerations in structural steel design. Behavior of reinforced and prestressed concrete elements and prestressed structures. Structural seismic design; elements of this design process to overcome the challenges inherent in major projects. Topics include overview of major projects, project context with architecture, design of foundations and structural systems, design project and team challenges and responsibilities. Students are required to prepare written reports and make oral presentations of selected cases.

CIEN E4242 Advanced design of steel structures  
3 pts. Lect: 3. Professor Aly and Mosq.  
Prerequisite: CIEN E4242 or instructor’s permission.  
CIEN E4242x is an introduction to the design of steel structures. Major topics include: behavior of steel components and structures, design of structural steel elements and composite steel members. Design of multi-story buildings and space structures. Continuous beams; composite construction; precasted slabs and columns.

CIEN E4217x Architectural design, computer graphics  
Prerequisite: CIEN E3141 or equivalent. CIEN E3142 or equivalent. Integrated methods of design and computer graphics. Use of graphic and computer-aided design and computer-aided design and architecture. Lectures on historical precedents on making space. Critical evaluation of electronic tools and current social importance. Labs on drafting and modeling software, physical modeling techniques and virtual reality.

CIEN E4204x Geotechnical engineering fundamentals  
3 pts. Lect: Professor L.  
Prerequisite: CIEN E3141 or instructor’s permission.  
CIEN E4204x 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 large structures and components. Performance of port and harbor facilities, evaluation and mitigation of liquefaction. Soil behavior, slope stability, onshore and offshore structures. Seismic earth pressures, slope stability, safety of dams and embankments, seismic code provisions and bridge design.  

CIEN E4243b Tunnel design and construction  
Engineering societys focus on multiple types of tunnel, including cut and cover tunnel, rock tunnel, cavern, immersed tube tunnel, and jacked tunnel. The design for the line, excavation, and instrumentation are also covered. A field trip or a project is expected.

CIEN E4236x Earth retaining structures  
Prerequisite: CIEN E3141 or instructor’s permission.  
CIEN E4236x 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 large structures and components. Performance of port and harbor facilities, evaluation and mitigation of liquefaction. Soil behavior, slope stability, onshore and offshore structures. Seismic earth pressures, slope stability, safety of dams and embankments, seismic code provisions and bridge design.
CIE E4235x Geotechnical engineering 3 pts. Lect: 3. Professor Pedron. Prerequisites: CHEM UN1403 or equivalent; ENME E3013x or ENME E3203x or instructor's permission. Course is designed for students interested in performing field investigations and design processes for the determination of subsurface conditions, and the application of deep foundations. CIE E4245x Civil systems and river hydraulics 3 pts. Lect: 2. Lab: 3. Not offered in 2020–2021. Prerequisites: CHEM UN1403 or equivalent; ENME E3013x or ENME E3203x or instructor's permission. Course is designed for students interested in performing field investigations and design processes for the determination of subsurface conditions, and the application of deep foundations. CIE E4250x Transportation and traffic engineering 3 pts. Lect: 3. Professor Slager. Prerequisites: CHEM UN1403 or equivalent; ENME E3013x or ENME E3203x or instructor's permission. Course is designed for students interested in performing field investigations and design processes for the determination of subsurface conditions, and the application of deep foundations.

CIE E4260x Environmental science and engineering 3 pts. Lect: 3. Professor Burian. Prerequisites: CHEM UN1403 or equivalent; ENME E3013x or ENME E3203x or instructor's permission. Course is designed for students interested in performing field investigations and design processes for the determination of subsurface conditions, and the application of deep foundations.
ENME E6216y Structural health monitoring
3 pts. Lect: 3. Professor Betti.
Prerequisites: 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 Random processes in mechanics

ENME E6315x Theory of elasticity

ENME E6320x Computational poromechanics
3 pts. Lect: 3. Professor Sun. 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 fluid 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. 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 E6364x Nonlinear computational mechanics

ENME E8310x Advanced continuum mechanics
3 pts. Lect: 3. Professor Dasgupta. Prerequisite: 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 E8320y Viscoelasticity and plasticity
4 pts. Lect: 3. Professor Dasgupta. Prerequisite: 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.

COURSES IN GRAPHICS

GRAP E2005 Computer-aided engineering graphics

GRAP E4005 Computer graphics in engineering
3 pts. Lect: 3. Professor Dasgupta. Prerequisites: 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.
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
**Computer Engineering Program: First and Second Years**

### Early-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><strong>Physics</strong> (five tracks, choose one)</td>
<td><strong>Chemistry</strong> (one semester lecture)</td>
<td><strong>University Writing</strong></td>
</tr>
<tr>
<td>MATH UN1101 (3)</td>
<td>ELEN E3081 (1)</td>
<td>ELEN E2101 (3)</td>
<td>CC1010 (3)</td>
</tr>
<tr>
<td><strong>CORE REQUIRED COURSES</strong></td>
<td><strong>REQUIRED LABS</strong></td>
<td><strong>Electives</strong> (total: 15 points)</td>
<td><strong>Electronic circuits lab</strong></td>
</tr>
<tr>
<td>ELEN E1201 (3.5)</td>
<td>ELEN E3081 (1.5)</td>
<td><strong>Early-Starting Students</strong></td>
<td><strong>COMPS W3101</strong></td>
</tr>
<tr>
<td>Intro. to elec. eng. (either semester)</td>
<td>Signals and systems</td>
<td><strong>COMPS W3203 (3)</strong></td>
<td><strong>ELEN E3082 (1)</strong></td>
</tr>
<tr>
<td></td>
<td>COMPS W3134 (3) or W3137 (4)</td>
<td>Design lab</td>
<td>Digital systems lab</td>
</tr>
<tr>
<td></td>
<td><strong>Data structures</strong></td>
<td><strong>ELEN E3101 (3)</strong></td>
<td><strong>HUMA CC1001</strong></td>
</tr>
<tr>
<td></td>
<td>CEEB W3087 (3)</td>
<td><strong>COMPS W3251 (4)</strong></td>
<td><strong>COCI CC1101</strong></td>
</tr>
<tr>
<td></td>
<td>Fund. of computer sys.</td>
<td><strong>ELEN E3084 (1)</strong></td>
<td><strong>HUMA CC1102</strong></td>
</tr>
</tbody>
</table>

### 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>CORE REQUIRED COURSES</strong></td>
<td><strong>Electives</strong></td>
<td><strong>Early-Starting Students</strong></td>
<td><strong>COMPS W4115 (3) Programming lang.</strong></td>
</tr>
<tr>
<td>IEER E3658 (3)</td>
<td><strong>Tech</strong></td>
<td><strong>COMPS W4118 (3) Operating systems</strong></td>
<td>(Electrical))</td>
</tr>
<tr>
<td>Probability</td>
<td><strong>COMPS W3201 (3)</strong></td>
<td><strong>COMPS W4118 (3)</strong></td>
<td>(Computer networks, EECS E4321 (3) Digital VLSI circuits, CSEE W4843 (3) Advanced logic design, CSEE W4844 (3) Computer architecture, CSEE W4840 (3) Embedded systems, CSEE W4848 (3) System-on-chip platforms**</td>
</tr>
<tr>
<td>COMPS W3157 (4)</td>
<td><strong>Nontech</strong></td>
<td><strong>COMPS W3101 (3)</strong></td>
<td><strong>CSEE W4119 (3) Computer networks, EECS E4321 (3) Digital VLSI circuits, CSEE W4843 (3) Advanced logic design, CSEE W4844 (3) Computer architecture, CSEE W4840 (3) Embedded systems, CSEE W4848 (3) System-on-chip platforms</strong></td>
</tr>
<tr>
<td>Advanced programming</td>
<td><strong>COMPS W3261 (3)</strong></td>
<td><strong>Circuit analysis</strong></td>
<td><strong>COMPS W4118 (3)</strong></td>
</tr>
<tr>
<td>ELEN E3081 (3.5)</td>
<td><strong>COMPS W3203 (3)</strong></td>
<td><strong>Circuit analysis lab</strong></td>
<td>(Electronic circuits lab)</td>
</tr>
<tr>
<td>Circuit analysis</td>
<td><strong>COMPS W3251 (2)</strong></td>
<td><strong>COMPS W3203 (4)</strong></td>
<td>(Electronic circuits lab)</td>
</tr>
<tr>
<td><strong>Total Points</strong></td>
<td><strong>市场需求</strong></td>
<td><strong>COMPS W3201 (3)</strong></td>
<td>(Electronic circuits lab)</td>
</tr>
</tbody>
</table>

For a discussion about programming languages used in the program, please see compeng.columbia.edu.

For a discussion about course content, please see compeng.columbia.edu.

Students are strongly encouraged 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 courses, ENGI E4000, as a graduation requirement. Ph.D. candidates are strongly encouraged to complete the course.

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1. ELEN E2101 may be replaced by MATH UN2020 (formerly MATH E1218) and either EEND E3101, or MATH UN2030, or COMPS W3237.
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 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>MATH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MATH UN101 (3)</td>
<td>MATH UN102 (3)</td>
<td>APMA E2000 (4) or either semester</td>
<td>APMA E2101 (3)</td>
</tr>
<tr>
<td><strong>PHYSICS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UN101 (5)</td>
<td>UN1402 (3)</td>
<td>Lab UN1404 (3) or chem. lab UN1500 (3)</td>
<td></td>
</tr>
<tr>
<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td>Lab UN1404 (3) or chem. lab UN1500 (3)</td>
<td></td>
</tr>
<tr>
<td>UN2081 (4.5)</td>
<td>UN2082 (4.5)</td>
<td>Lab UN3061 (2) or chem. lab UN1500 (3)</td>
<td></td>
</tr>
<tr>
<td><strong>CHEMISTRY</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>one-semester lecture (3–4)</td>
<td>UN403 or UN404 or UN204 or UN104</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lab: UN1500 (3) or physics lab UN-403 (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CORE REQUIRED COURSES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E1201 (3.5)</td>
<td>Intro. to elec. eng. (either semester)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC1010 (3)</td>
<td>或 either semester</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>REQUIRED NONTECHNICAL ELECTIVES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HUMA CC101, COCI CC101, or Global Core (3–4)</td>
<td>HUMA CC101, COCI CC101, or Global Core (3–4)</td>
<td>ECON UN1105 (4) and UN115 recitation (8)</td>
<td></td>
</tr>
<tr>
<td>HUMA UN1121 or UN1123 (3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COMPUTER SCIENCE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGS E1006 (5)</td>
<td>COMS W1004 (5) or W1007 (5)</td>
<td>W3203 (3) Data structures</td>
<td></td>
</tr>
<tr>
<td><strong>PHYSICAL EDUCATION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UN1001 (1)</td>
<td>UN1002 (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>THE ART OF ENGINEERING</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGS E1102 (4)</td>
<td>Or either semester</td>
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</tr>
</tbody>
</table>

### COMPUTER ENGINEERING: THIRD AND FOURTH YEARS

#### LATE-STARTING STUDENTS

<table>
<thead>
<tr>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CORE REQUIRED COURSES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EIDR E3658 (3) Probability</td>
<td>COMS W3157 (4) Advanced programming</td>
<td>COMS W4118 (2) Operating systems</td>
</tr>
<tr>
<td>COMS W3134 (3) or W3157 (4) Data structures</td>
<td>ELEN E3301 (3) Electronic circuits</td>
<td>or COMS W4115 (2) Programming lang.</td>
</tr>
<tr>
<td>ELEN E3001 (3.5) Circuit analysis</td>
<td>COMS W3261 (2) Models of comp.</td>
<td>(Choose 3 of 6)</td>
</tr>
<tr>
<td>ELEN E3101 (2) Signals and systems</td>
<td>CSEE W3627 (3) Fund. of computer systems</td>
<td>CSEE W4421 (3) Computer networks, EECS E4201 (3) Digital VLSI circuits, CSEE W4432 (3) Advanced logic design, CSEE W4424 (3) Computer architecture, CSEE W4840 (3) Embedded systems, CSEE W4968 (3) System-on-chip platforms</td>
</tr>
<tr>
<td><strong>REQUIRED LABS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEN E3081 (1) Circuit analysis lab</td>
<td>ELEN E3083 (1) Electronic circuits lab</td>
<td>ELEN E3082 (1) Digital systems lab</td>
</tr>
<tr>
<td>ELEN E3064 (1) Signals and systems lab</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### ELECTIVES

- **MATH**: 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.
- **COMS W3261** can be taken one semester later than pictured.
- If possible, ELEN E3201 and ELEN E3204 should be taken along with ELEN E320 and ELEN E3301, respectively, and ELEN E3003 and ELEN E3002 taken with ELEN E3301 and CSEE W3207 respectively.
- The total points of technical electives to be reduced to 13 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.
- Assuming technical electives taken Semesters VII and VIII, and 9 points of nontechnical elective taken Semesters VI, VII, and VIII.

#### TECH

- 15 points required; see details within the text

#### NONTECH

- Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement) or seas.columbia.edu for details (administered by the advising dean)

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1. APMA E2101 may be replaced by MATH UN102 (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 W3230) and electronic 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.  
3. 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 ECR E3858 and augment it with ECR E3807.  
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 elective taken Semesters VI, VII, and VIII.

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**Core Computer Engineering Courses**  
CSEE W4119: Computer networks  
CSEE W4140: Networking laboratory  
ECECS E4321: Digital VLSI circuits  
ECECS E4740: Hybrid comp. for sig. & data proc.  
ECECS E6744: Int. – Intelligent & connected syst.  
ECECS W4426: Advanced logic design  
ECECS W4440: Computer architecture  
ECECS W4460: Embedded systems  
ECECS W4468: Systems-on-chip platforms  
ECECS E4941: Wireless networks & systems  
ECECS E6181: Modeling & performance eval.  
ECECS E6201: Adv. digital electronic circuits  
ECECS E6202: VLSI hard. arch. for sig. proc. & ml  
CSEE E6402: Hardware security  
ECECS E6746: Internet of things—sys. & physical data analytics  
CSEE E6864: Parallel computer architecture  
CSEE E6866: CAD of digital systems  
CSEE E6869: Formal verification of hardware/software systems  
CSEE E6868: Embedded scalable platforms

The overall program must include at least 12 points of 6000-level ELEN, ECECS, 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) 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.

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**Electives**  
- 15 points required; see details within the text

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**Core Requirements**  
- 15 points required; see details within the text

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**Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement) or seas.columbia.edu for details (administered by the advising dean)**

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For a discussion about programming languages used in the program, please see compeng.columbia.edu.
The function and influence of the computer is pervasive in contemporary society. Today’s computers process the daily transactions of international banks, the data communications satellites, the images in video games, and even the fuel and ignition systems of automobiles. The computer is also a core component 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 is a comprehensive program that covers both theoretical computer science and mathematics and on applications 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 optimization methods, computer architecture, computer-aided design, computer communications, databases, mathematical models for computing, optimization, and software systems.

Laboratory Facilities

The department has well-equipped lab areas for research in computer graphics, computer-aided design, computer vision, databases and digital libraries, data mining and knowledge discovery, distributed systems, mobile and wearable computing, natural language processing, networking, operating systems, programming systems, robotics, user interfaces, real-time multimedia, and speech research. The labs for research in image processing, vision, graphics, and robotics contain specialized equipment such as the Baxter Research Robot, PR2 mobile robot manipulator, Laurel P200 robotic arm, microphone array, custom-built overhead XYZ gantry robot, Toshiba RMA manipulator, Barrett Telemanipulator, robots in the RW100 mobile robots, 1 Evolution ER-1 robot, 1 RAVI-TR2 mobile robot with RTK GPS, and software in as many as 100 laboratory servers, real-time imaging boards, a number of 3D printers such as the Ultimaker, Autodesk Ember and professional audio recording devices; a networking testbed with Cisco backbone routers, traffic generators; an IDS testbed with several IDS sensors and intrusion detection systems, and Linux servers; a simulation testbed with several Linux servers and Cisco router testbeds. The department uses a SAP, IP phone system. The protocol was developed in the department.

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, and partially in theoretical computer science and mathematics. Thus, students obtain the background needed 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 in advance faculty research projects using state-of-the-art computing facilities. Qualifying majors sometimes serve as consultants at Columbia University Information Technology (CULIT), which operates several computer labs at convenient locations on campus.

Upper-level students in computer science may assist faculty members with research projects, particularly in the development of software. Ongoing faculty projects include algorithmic analysis, computational complexity, software tool design, distributed computation, modeling and performance evaluation, computer networks, architectural CAD, digital systems, computer graphics, programming environments, expert systems, natural language processing, computer vision, robotics, computational biology, computer security, multiuser systems, and intelligent interfaces. VLSI applications, artificial intelligence, combinatorial modeling, virtual environments, and related software applications. 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 or closely related disciplines. Others pursue advanced degrees and/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: 5 Engr Courses, which is a prerequisite to the CS major, the CS Core consisting of 7-8 classes (24-25 points), 7 undergraduate 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 requirements must be approved by the faculty adviser. All the 6 predefined tracks are as follows:

- Foundations of Computer Science
- Software, systems, 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, special topics, and general technical electives must also be approved by the faculty adviser.

Prerequisite to the CS major

The major in computer science at Columbia consists of an 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 9 or 10 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 W1104 or W1107 (3)
2. ENGI E1006 (3)
3. COMS W3134 (3) or W3137 (4)
4. COMP S2001 (3)
5. COMS W3251 (4)
6. CSEE W3827 (3)
7. STAT GU4001 or ECON E1410 (3)

Tracks

In addition, an advanced track is available by invitation qualified students who desire an extra opportunity for specialization. Any course exceptions to the requirements must be approved by the faculty adviser. All the 6 predefined tracks are as follows:

- Foundations of Computer Science
- Software, systems, special topics, and general technical electives must also be approved by the faculty adviser.

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 written report is mandatory and an oral presentation may also be required.

General Technical Electives

An additional 15 points of advisor approved general technical electives at the 2000 level or above are required. These general technical electives should be in mathematics, science, engineering or closely related disciplines.

Advanced Placement

Students who pass the Computer Science Advanced Placement (AP) Exam in 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
### COMPUTER SCIENCE PROGRAM: FIRST AND SECOND YEARS

<table>
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<tr>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
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<tbody>
<tr>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4)</td>
<td>HUMA CC1102 or COCI CC1102 or Major Cultures (3–4)</td>
</tr>
<tr>
<td>PHYS UN1401 (3) or UN1402 (3)</td>
<td>UN1401 (3.5) or UN1402 (3.5)</td>
<td>Chemistry or physics lab: PHYS UN1404 (3) or PHYS UN1401 (2) or CHEM UN1502 (3) or CHEM UN1507 (2) or CHEM UN1505 (4)</td>
<td>HUMA UN1121 or UN1122 (3)</td>
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<tr>
<td>CHEM UN1403 (3) or higher or EEEB UN2001 (4) or UN2005 (4) or higher other semester</td>
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<tr>
<td>CC1010 (3) or other semester</td>
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<tr>
<td>ECON UN1105 (4) and UN1106-rotation (3) or any semester</td>
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**REQUIRED**

- **COMPUTER SCIENCE**
  - COMS W1014 (3) or COMS W1017 (3) or Object-oriented programming and other semester

**TECH ELECTIONS**

- ENG E1103: Computing for EAS (3) or other semester

**PHYSICAL EDUCATION**

- UN1001 (1) or UN1002 (1)

**THE ARt OF ENGINEERING**

- ENGI E1102 (4) or other semester

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### COMPUTER SCIENCE: THIRD AND FOURTH YEARS

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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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<tbody>
<tr>
<td>COMS W3261: Introduction to modern analysis I</td>
<td>MATH GU4155: Probability theory</td>
<td>MATH GU4155: Probability theory</td>
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<tr>
<td>COMS W4232: Computational learning theory</td>
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</tr>
<tr>
<td>APMA E4300: Numerical methods</td>
<td>IEDR E4407: Game theoretic models of operation</td>
<td>IEDR E4407: Game theoretic models of operation</td>
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<tr>
<td>CSCI GU4191: Software engineering</td>
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<tr>
<td>COMS W4901: Projects in computer science*</td>
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<tr>
<td>COMS W4906: Special topics in computer science</td>
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**ELECTIVES**

- **TECH**
  - 6 points

- **NONTECH**
  - 3 points

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**Note:** No more than 6 points of project/thesis courses (COMS W3902, W3906, W4901) can count toward the track.

**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

- CSEE W4118: Computer networks

**ELECTIVES:**

- 12 points from the following list:

  - COMS W3803: Undergraduate thesis*
  - COMS W3806: Undergraduate projects in computer science*

  - Any COMS W41xx course

**TOTAL POINTS**

- 15-16

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**Track 3: Intelligent Systems Track**

The intelligent systems track is for students interested in machine learning, robotics, 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 W4751: Artificial intelligence
  - COMS W4705: Natural language processing
  - COMS W4795: Spoken language processing
  - COMS W4731: Computer vision
  - COMS W4723: Computational aspects of robotics
  - COMS W4771: Machine learning

**ELECTIVES:**

- 12 points required

- Up to 12 points from the following list:

  - COMS W4145: Final processing
  - COMS W4122: Computational learning theory

  - Any COMS W49xx course (with adviser approval)

  - Any COMS W49xx course (with adviser approval)

**TOTAL POINTS**

- 15

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**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 W4115: Programming languages and translators

- COMS W4170: User interface design

**ELECTIVES:**

- 15 points from the following list:

  - COMS W3902: Undergraduate thesis*
  - COMS W3906: Undergraduate projects in computer science*

  - Any COMS W44xx course

  - Any COMS W47xx course (with adviser approval)

**TOTAL POINTS**

- 15

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**Track 5: Vision, Interaction, Graphics, and Robotics Track**

The vision, interaction, graphics, and robotics track focuses 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...
**COMPUTER SCIENCE PROGRAM: FIRST AND SECOND YEARS**

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<tbody>
<tr>
<td>MATHEMATICS</td>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4)</td>
</tr>
<tr>
<td>PHYSICS (three tracks, choose one)</td>
<td>UN1401 (3)</td>
<td>UN1601 (3.5)</td>
<td>UN1501 (3.5)</td>
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<td></td>
<td>UN1402 (3.5)</td>
<td>UN1502 (3.5)</td>
<td>UN1502 (4.5)</td>
</tr>
<tr>
<td>CHEMISTRY/BIOLOGY (choose one course)</td>
<td>CHEM UN1403 (3) or higher</td>
<td>or EEEB UN2001 (4) or UN2005 (4) or higher</td>
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<tr>
<td>UNIVERSITY WRITING</td>
<td>CC1010 (3) or other semester</td>
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<tr>
<td>REQUIRED NONTECHNICAL ELECTIVES</td>
<td>HUMA CC1101 or ECON UN1105 (4) and UN1105 recitation (3) or any semester</td>
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</tr>
<tr>
<td>REQUIRED TECH ELECTIVES</td>
<td>ENGI E1006: Computing for EAS (3) or other semester</td>
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<tr>
<td>COMPUTER SCIENCE</td>
<td>COMS W1104 (3) or COMS W1107 (3) or Object-oriented programming or other semester</td>
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<td></td>
<td>COMS W1314 (3) or COMS W1317 (4) or Data structures and CSCI W3203 (3) or Discrete math</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) or other semester</td>
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</table>

- **MATH UN1101**: Calculus I
- **MATH UN1102**: Calculus II
- **APMA E2000**: Applied Calculus
- **ENGI E1006**: Computing for EAS
- **COMS W1104** or **COMS W1107**: Introduction to computer science
- **COMS W1314** or **COMS W1317**: Data structures and CSCI W3203
- **ENGI E1006**: Computing for EAS
- **ENGI E4150**: Introduction to computer science

**ECON UN1105**: Microeconomics

**HUMA CC1101**: Introduction to computer science

**EEEB UN2001**: Object-oriented programming

**UN1001**: Physical education

**UN1002**: Physical education

**ENGI E1102**: Computing for EAS

**COMS W1104** or **COMS W1107**: Introduction to computer science

**COMS W1314** or **COMS W1317**: Data structures and CSCI W3203

**UN1001**: Physical education

**UN1002**: Physical education

**ENGI E1102**: Computing for EAS

**COMS W1104** or **COMS W1107**: Introduction to computer science

**COMS W1314** or **COMS W1317**: Data structures and CSCI W3203

**UN1001**: Physical education

**UN1002**: Physical education

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**UN1001**: Physical education

**UN1002**: Physical education

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**COMS W1314** or **COMS W1317**: Data structures and CSCI W3203

**UN1001**: Physical education

**UN1002**: Physical education

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**COMS W1314** or **COMS W1317**: Data structures and CSCI W3203

**UN1001**: Physical education

**UN1002**: Physical education

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**COMS W1314** or **COMS W1317**: Data structures and CSCI W3203

**UN1001**: Physical education

**UN1002**: Physical education

**ENGI E1102**: Computing for EAS
except possibly for summer internships
students spend at least half of their
research throughout the program. Ph.D.
original research, which is supervised by
that students learn best by doing
program is research, with the philosophy
encouraged to pursue research if they
member. Students in all the tracks are
a subfield and write an M.S. thesis,
who want to do extensive research in
of the M.S. Thesis track for students
Admitted students will enroll for
a total of four semesters covering a course
numbers for which no designer is indicated: NOTE: Students may receive
in addition to the seminar requirements. In
adding classes already
offered at the journalism and
engineering, students will attend a seminar and workshop
designed specifically for the joint program. The seminar 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 of journalism from concept to
development, the influence of social media;
the changing business models of journalism
process; the influence of social media;
the changing business models of journalism;
the changing business models of journalism;
the changing business models of journalism;
the changing business models of journalism;
Prerequisite: Instructor’s permission. Design, development, and implementation of operating systems. Prerequisite: Experience in Java, basic knowledge of C, Linux, Windows, and Unix/Linux. Emphasis on warehouse scale computing systems. Introduction to current storage systems, hardware and software techniques for data center computers. Significant implementation is required: the final project involves writing an interactive 3D video game in OpenGL.

COMS W4162c Advanced computer graphics 3 pts. Lect. 3. Professor Zhang.
Prerequisite: COMS W4160 or equivalent, or instructor’s permission. A second course in computer graphics. Introduction to advanced topics in image and signal processing, geometric modeling with meshes, advanced image synthesis including ray tracing and global illumination, and other related topics.

COMS W4180c Security I 3 pts. Lect. 3. Professor Jane.
Prerequisite: COMS W1917 or equivalent. Introduction to computer security. Security on the Internet, and modern algorithmic ideas central to many computer engineered systems. General introduction to security. How vulnerabilities, both on implementation of systems and important mathematical and geometric concepts such as Fourier analysis, mesh algorithms and subdivision, and global illumination.

COMS W4167x or y Computer animation 3 pts. Lect. 3. Professor Chow.
Prerequisite: COMS W4162x or y and non-programming. Shares lectures with ECBM E3060, but the work requirements differ somewhat. May be repeated for credit, although the area is emphasized on data center computers.

COMS W4162x or y Advanced computer graphics 3 pts. Lect. 3. Professor Zhang.
Prerequisite: COMS W4160 or equivalent, or instructor’s permission. A second course in computer graphics. Introduction to advanced topics in image and signal processing, geometric modeling with meshes, advanced image synthesis including ray tracing and global illumination, and other related topics.
COMS W4210 Numerical algorithms and complexity 3 pts. Lect: 3. Instructor: To be announced. Prerequisite: CSC E1105. A rigorous introduction to the design and analysis of algorithms and computational complexity. Focus on algorithm design and analysis, asymptotic analysis and other computational hardness, and open-ended optimization and computational hardness. Topics include sorting, searching, graph theory, dynamic programming, and evolutionary strategies, as well as dynamic programming and, and underlying assumptions and limitations of different modes of computation and computational speedup in audio, image, and video processing units (GPGPUs) and heterogeneous computing environments.

MECS E4610x Evolutionary computation and design automation 3 pts. Lect. 3. Professor Lupan. Prerequisite: Basic programming experience in any language. Fundamental and advanced topics in the field of evolutionary computation, including representation and encoding, fitness evaluation, genetic operators, and algorithm convergence. Applications to design optimization and other optimization problems in AI (including vision, natural language processing, and robotics) as time permits.

MECS W4733x or y Biometrics 3 pts. Lect. 3. Professor Pe'er. Prerequisite: COMS W3134, W3135, or W3137 (or equivalent) or instructor’s permission. The mathematical theory and applications of biometric recognition systems. Survey and analysis of architecture, algorithms, and underlying assumptions and limitations of different modes of computation and computational speedup in audio, image, and video processing units (GPGPUs) and heterogeneous computing environments.

COMS W4741x or y Natural language processing 3 pts. Lect. 3. Professor Colin McColloch. Prerequisite: COMS W3134, W3135, or W3137 (or equivalent) or instructor’s permission. The use of computational tools for exposure to AI at machine learning. Topics include feature extraction, classification, machine learning, 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.

Biometrics: Introduction to biometric systems and applications. 3 pts. Lect: 3. Professor Pe'er. Prerequisite: COMS W3134, W3135, or W3137 (or equivalent) or instructor’s permission. The mathematical theory and applications of biometric recognition systems. Survey and analysis of architecture, algorithms, and underlying assumptions and limitations of different modes of computation and computational speedup in audio, image, and video processing units (GPGPUs) and heterogeneous computing environments.

COMS W4737x or y Biometrics 3 pts. Lect. 3. Professor Salleb-Aouissi. Prerequisite: COMS W3134, W3135, or W3137 (or equivalent) or instructor’s permission. The mathematical theory and applications of biometric recognition systems. Survey and analysis of architecture, algorithms, and underlying assumptions and limitations of different modes of computation and computational speedup in audio, image, and video processing units (GPGPUs) and heterogeneous computing environments.

Biometrics: Computer vision techniques. 3 pts. Lect: 3. Professor Pe'er. Hours: 7. Prerequisites: Computer science background, exposure to AI or machine learning. Topics include image processing, object recognition, vision systems (e.g., brightness and reflectance, shape from shading and segmentation, pattern classification methods, optical flow and motion, 2D and 3D object representation, object recognition, vision systems and applications.

MECS W4733x or y Computational aspects of robotics 3 pts. Lect. 3. Professor Alon. Prerequisite: COMS W3134, W3135, or W3137 (or equivalent) or instructor’s permission. The use of computational tools for exposure to AI at machine learning. Topics include feature extraction, classification, machine learning, 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.
dimensional analysis. Topics include high-dimensional probability, theory of generalization and generalization bounds, online learning and optimization, spectral analysis.

COMS W4774y Unsupervised learning 3 pts. Lect: 3. Professor Gravano. Prerequisite: 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 principal component analysis, dimensionality reduction and density estimation. Topics include clustering via k-means, hierarchical clustering, spectral clustering, k-means clustering with various forms of feedback, good initialization strategies, 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, ISOMAP, and study of ambulatory sensor data. Content of the course will reflect the current state of theoretical guarantees one can provide about such techniques. Miscellaneous topics include: dimensionality analysis of data structures for fast nearest neighbor search such as Cover Trees and LOAF. Multi-core programming and systems-on-chip. Platform architectures for embedded, mobile, and cloud computing.

COMS W4840y Online and adaptive control 3 pts. Lect: 3. Professor Paul. Prerequisite: 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 microcontroller-based embedded system including at least one custom peripheral. Knowledge of digital design and logic design required. Lab required.

COMS E6113y Topics in database systems 3 pts. Lect: 2. Professor Bednarek. Prerequisites: At least one COMS W41xx or COMS W4995 when the special topic extends to network security, privacy, sustainability, and societal issues. Reviews established results and state-of-the-art research. Focus changes frequently to remain timely. Recent offerings have included applied cryptography, modern software architectures such as Approximate Correct, and exact learning. This course can be repeated for credit. Recent offerings have included hardware and cognitive computing, sensor security. The state of threats against computers, and social consequences.

COMS E6185x or y Intrusion and anomaly detection 3 pts. Professor Stolfo. Prerequisite: COMS W4180 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 neighbor search in mobile and wearable. Ubiquitous/pervasive computing. Collaboration with other users. Display, interaction, and communication technologies. Sensors for tracking position, orientation, motion, environmental and physiological signals. Text-based applications and social consequences. COMS E6180y Modeling and performance 3 pts. Lect: 2. Professor Mao. Pre- or corequisite: COMS W4180 Network security. Provides a detailed treatment for network and host-based intrusion detection and intrusion prevention systems. Content of this course can be repeated for credit. Recent offerings have included modern software architectures such as Approximate Correct, and exact learning. This course can be repeated for credit. Recent offerings have included hardware and cognitive computing, sensor security. The state of threats against computers, and social consequences.

COMS E6222x or y Analysis of algorithms, 3 pts. Lect: 2. Professor Malkin. Prerequisite: CSOR W4231 or equivalent. In-depth study of inherent abilities and limitations of computationally efficient learning algorithms. Algorithms for learning rich Boolean functions classes in online, Probably Approximately Correct, and exact learning models. Content of the course changes each time it is offered. The state of threats against computers, and social consequences.

COMS E6252x y Advanced topics in cryptographic theory 3 pts. Lect: 2. Professor Bednarek. In-depth study of inherent abilities and limitations of computationally efficient learning algorithms. Algorithms for learning rich Boolean functions classes in online, Probably Approximately Correct, and exact learning models. Content of the course changes each time it is offered. The state of threats against computers, and social consequences.

COMS E6995x or y Topics in computer graphics 3 pts. Lect: 3. Professor Yang. Prerequisites: COMS W4188, W4191, W4195, or W4179, or significant software development experience. Topics include architectural design of modern computer graphics hardware repair, concurrent software reliability, software error detection, and more. COMS E6996x or y Topics in networking 3 pts. Lect: 2. Professor Jain. Prerequisites: COMS W4180, CSEE W4199 and W4261 recommended. Review of recent applications and future research directions.
COMS E6117y or Theoretical topics in computer science
3 pts. Lect: Prof. Servedio. Prerequisite: Instructor’s permission. Concentration on some theoretical aspects of computer science. Content varies from year to year. May be repeated for credit.

ECEC 6352 Advanced digital electronic circuits
3 pts. Lect: Prof. S. Sakak. Prerequisite: ECEC 6351. Advanced topics in digital system theory and nonconventional logical circuits. Timing styles. Latches and flip-flops, loops, delay locked loops, SRAM and DRAM memory circuits. Modeling and analysis of on-chip interconnection. Advanced technology issues that affect circuit design. The class may include a team circuit design project.

COMS E6414x Hardware security
3–6 pts. Members of the faculty. Prerequisite: CSEE W3807 and COMS W3167. Recommended: CSEE W449x and COMS W4417. Techniques for securing the fundamental aspects of all computing devices and systems. Topics include: hardware security, hardware supply chain trust and security, stressors in hardware security, attacks on the board (i.e., side channel attacks and defenses), hardware support for formalization, attack faults and defenses, hardware support for software security, safety, control flow integrity, information flow tracking, diversity, side-channel attack mitigation. Hardware support for accelerating cryptography and applied cryptography.

CSEE W6960x or From data to solutions 3–6 pts. Lect: Prof. C. Carloni. Prerequisites: Familiarity with common data science methods and tools. Must be able to write clearly and concisely. Covers topics in machine learning, statistics, data mining, linear algebra, and numerical linear algebra. Topics include: random walks, graph clustering, spectral graph theory, matrix completion, compressed sensing, manifold learning, and deep learning. Students will work on projects in their own research area.

STCS G4014x or Foundations of computational complexity
3 pts. Lect: Prof. B. Blais. Prerequisites: Basic probability and statistics, calculus, and some optimization. Ability to write software to analyze data. Knowledge of programming language and statistics for machine learning, such as 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 techniques. Weekly papers, assignments, and final project required.

COMS E6717y Humanoid robots
3 pts. Lect: Prof. A. Allen. Prerequisite: A course in at least one of the following: AI, robotics, computer graphics, or computer vision. Seminar on humanoid robotics. Analysis of existing hardware and software platforms. Programming of multi-degree-of- freedom robots. Understanding sensor feedback in precise (act-sense-act) control paradigms. Learning theory, planning and reasoning. Final project includes implementing a humanoid robot on either simulated or physical robot.

COMS E6729x or y Computational imaging 3 pts. Lect: Prof. N. J.ayar. Prerequisites: COMS W4711 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, catastrophic imaging, high dynamic range imaging, etc. How they are sometimes related. Grading will be based on homework, class participation, projects, and a final exam. Students will be required to present a final project.

COMS E6729x or y 3D photography 3 pts. Lect: Prof. A. Allen. Prerequisite: Experience with at least one of the following topics: Computer graphics, computer vision, signal processing, robotics or computer-aided design, or permission of instructor. Programming proficiency in C, C++, or JAVA. 3D Photography—The process of automatically creating 3D computer-tailored models of objects in detail. Applications include robotics, medicine, graphics, virtual reality, entertainment and digital cinema, 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 E6729y Computational photography 3 pts. Lect: Prof. B. B. Bhattacharyya. Prerequisites: COMS W4610, W4171, or a working knowledge of photography is recommended. Students should have knowledge in any of these 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 segmentation, camera lens arrays, programmable lighting, face detection, single and multi-view geometry, and more.

COMS E6715y Visual databases 3 pts. Lect: Prof. K. K. Chaudhuri. Prerequisites: COMS W4113, W4131, or W4137 (or equivalent). COMS W4715 and W4735 helpful but not required. Contact instructor if uncertain. The retrieval and analysis of large volumes 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 frames; motion: machine learning methods for classification. Mid-level processing: content-based retrieval, similarity measures. Human perception (home, educational, self-taught, sports, talk shows), edited (news, drama), human memory limits; progressive refinement; visualization techniques; incorporation of audio and fast. High-level processing: extraction of thematic structures, ontologies, semantic filters, and learning. Summary of personalizations and summarizations; deletion of pacing and emphasis and demonstrations from commercial and research systems throughout. Substantial course project or term paper required.

COMS E6737x or y Biometrics 3 pts. Lect: Prof. B. Behfar. Prerequisites: COMS W4711 or instructor’s permission. A survey of some of the major approaches to biometric identification and personal recognition. New courses and design of a new course including security and liveness detection, single and multiview geometry, and more. Camera lens arrays, programmable lighting, face image-based rendering, motion magnification, feature matching using RANSAC, image mosaics, representations. Topics include HDR imaging, used to produce a new level of images and visual representations. Here the design and analysis of correct (i.e., bug-free) concurrent and embedded hardware/software systems. Topics include temporal logic: model checking; deadlocks and livelocks; fairness; computability (SAT, checking); 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).

CCEE E6636x Formal verification of hardware and software systems 3 pts. Lect: Prof. S. Theobald or H. R.ing. Prerequisites: COMS W3134, W3137 or W3261. Introduction to the theory and practice of formal verification. Here the design and analysis of correct (i.e., bug-free) concurrent and embedded hardware/software systems. Topics include temporal logic: model checking; deadlock and livelock issues; fairness; computability (SAT, checking); 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).

CCEE E6636x or Embedded scalable platforms 3 pts. Lect: Prof. S. Theobald or H. R.ing. Prerequisites: COMS W4228 or W4830, or equivalent. Topics include: computer principles, machine organization and design of computer systems; integrated circuit design and fabrication; computer architecture; computer arithmetic; processor design methods, synchronization, data coherence and interconnection networks. Performance analysis of computer systems.

CCEE E6647y Distributed embedded systems 3 pts. Lect: Prof. P. Prakash. Prerequisites: Any COMS W411X, CSEE W488X, CSEE E485X or E3344X course, or instructor’s permission. An interdisciplinary graduate-level seminar on system 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 design of embedded computing systems. Substantial reading of research papers, class participation, and semester-long project.

COMS E6938y or Speech recognition 3 pts. Lect: Prof. M. A. Blatt. Prerequisites: 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 E699x and Y Directed research in computer science 1–3 pts. Members of the faculty. Prerequisites: Submission of outline of proposed research for approval by faculty member who will supervise. The department must approve the number of credits. May be repeated for credit. Only for Ph.D. and S.C. candidates.

COMS E6910x and Graduate research, I 1–6 pts. Members of the faculty. Prerequisites: 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. No research credit will be required. May be taken over more than one semester, until at least 12 points have been completed. No more than 12 points of COMS E6910 may be taken. Consult the department for sation assignment.

COMS E6912x and Thesis I 1–3 pts. Members of the faculty. Prerequisite: COMS E6910. 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 final written report is essential and will include the student's original contribution. Final report required. May not be taken for pass/fail credit or as an audit.

COMS E6915y Technical writing for computer scientists and engineers 1 pt. Members of the faculty. Prerequisites: Submission of an outline of the proposed research for approval by faculty adviser. Only for M.S. students in the Computer Science Department who need relevant work experience as part of their program. Final report required. May not be taken for pass/fail credit or as an audit.

COMS E6916x Technical writing for computer scientists and engineers 1 pt. Members of the faculty. Prerequisites: Instructor’s permission. Intermediate 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 design of embedded computing systems. Substantial reading of research papers, class participation, and semester-long project.

COMS E6938x and Topics in computer science 1–3 pts. Members of the faculty. Prerequisites: Submission of outline of proposed research for approval by faculty member who will supervise. The department must approve the number of credits. May be repeated for credit. Only for Ph.D. and S.C. candidates.

COMS E6916x and Topics in computer science 1–3 pts. Members of the faculty. Prerequisites: Submission of outline of proposed research for approval by faculty member who will supervise. The department must approve the number of credits. May be repeated for credit. Only for Ph.D. and S.C. candidates.

COMS E6918x and Topics in computer science 1–3 pts. Members of the faculty. Prerequisites: Submission of outline of proposed research for approval by faculty member who will supervise. The department must approve the number of credits. May be repeated for credit. Only for Ph.D. and S.C. candidates.
EARTH AND ENVIRONMENTAL ENGINEERING

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 School of Mines of Columbia University 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 honors council. You can see the bronze statue of The Founders of Mines located in the 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, Lavin Duddleson Krumb. HKSM has been a leader in mining and metallurgy research and education, including the first mining handbook by Professor Peet, the first mineral processing handbook by Professor Taggart, and other pioneering work in mineral beneficiation, chemical thermodynamics, kinetics, transport phenomena, extraction and processing, and environmental and environmentally responsible mining, and pursuit of state-of-the-art research advancing responsible use of our earth 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. The Henry Krumb School of Mines located in The Fu Foundation School of Engineering and Applied Science (SEAS) has three units:

• The Department of Earth and Environmental Engineering (eee.columbia.edu) (EEE):
  - With the creation of the Earth and Environmental Engineering Department 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 nineteenth to encompass environmental concerns related to the use of materials, energy and water resources, and to reflect one of the major thrusts of SEAS with a focus on the development and application of technology for the sustainable development, use and integrated management of Earth’s resources.
  - Columbia’s interdepartmental program in Materials Science and Engineering (matsci.columbia.edu) (MSE) is the successor of the HKSM Materials Science and Engineering program and focuses on the design of advanced materials and the effects of composition and processing on material properties. This program, administered by the Department of Applied Physics and Applied Mathematics, is described on page 177.
  - The Earth Engineering Center (seas.columbia.edu/earth) is the engineering unit of the Earth Institute and is dedicated to directing engineering research toward the reconfiguring of industrial activities with full understanding of their environmental impacts. Several faculty of the HKSM are associated with the Earth Engineering Center.

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 Engineering Research and the B.S. program in Earth and Mineral 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.

EARTH AND ENVIRONMENTAL ENGINEERING

Starting in 1996, the educational programs of Columbia University in mining and mineral engineering were transformed into the present program in Earth and Environmental Engineering (EEE). This program is concerned with the environmentally sound extraction and processing of raw materials (minerals, fuels, water), the management and development of land and water resources, and the recycling or disposal of used materials. EEE offers the Bachelor of Science (B.S.) in Earth and Environmental Engineering, the Master of Science (M.S.) in Earth and Environmental Engineering, and the doctorate degree (Ph.D., Eng.Sci.) in EEE.

The EEE program welcomes Combined Plan students. An EEE minor is offered to all Columbia engineering students who want to enrich their academic record by concentrating some of their technical electives on Earth/Environmental subjects. There is close collaboration between EEE and the Departments of Civil Engineering and Earth and Environmental Sciences, including several joint appointments.

RESEARCH CENTERS ASSOCIATED WITH EARTH AND ENVIRONMENTAL ENGINEERING

Columbia Water Center. The Center was established in 2008 to address Global Water Security. It currently has 3 major initiatives:

- The Global Water Sustainability Initiative is focused on an assessment of global water scarcity and risk, and innovations across scales, from farmer’s field to reservoir optimization to national policy modifications to international trade, to develop real world solutions to an impending global water crisis.
- The Global Flood Initiative recognizes that all natural hazards, floods are responsible for the largest average annual loss of property and life. They are also a significant contributor to pollutant loading and environmental impacts on watersheds. In a globalized society, the disruption of food, energy, and manufactured goods supply chains by floods has also emerged as an issue. The initiative is developing state-of-the-art climate analyses for global flood risk projection, its mapping onto supply chains, and risk management using novel structural and financial tools.

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.” The mission of the Center is to guide technology and energy policy decisions with data-based, well-balanced, and transparent descriptions of the environmental profiles of energy generation and storage systems in current and future electricity grids. Current research thrusts include:

- Solar energy grid integration
- The CLCA is engaged in model development and environmental systems analyses of renewable energy integration into
Brookhaven National Laboratory and several European, South American, and Asian institutions.

Earth Engineering Center (EEC) has concentrated on advancing the goals of sustainable waste management in the U.S. and globally. Economic development has resulted in the generation of billions of tons of used materials that can be a considerable resource, but when not managed properly, constitute a major environmental problem both in developed and developing nations. In 2003, in collaboration with the Energy Recovery Council of the U.S., EEC developed the Waste to Energy Research and Technology Council (WERTC). As of 2013, the Global WERTC Council (www.wertc.org) has sister organizations in 14 countries including Canada, China, Germany, Greece, India, Italy, Mexico, and the U.K. EEC conducts a biannual survey of waste management in the 50 states of the Union.

Industry/University Cooperative Research Center for Particulate and Surfactant Systems (CPaSS). CPaSS was established in 1988 by the Henry Krumb School of Mines, Department of Chemical Engineering, and Department of Chemistry at Columbia University. The Center encompasses detailed structure-property assessment of several classes of surface-active molecules, including oligomeric, polymeric, and biomolecules. The aim of CPaSS is to develop and characterize novel surfactants for industrial applications such as coatings, dispersions, deposition, gas hydrate control, personal care products, soil decontamination, waste treatment, corrosion prevention, filtration, and controlled chemical reactions.

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.

International Research Institute for Climate Prediction (IRI). The IRI is the world’s leading institute for the development and application of seasonal to interannual climate forecasts. The mission of the IRI is to enhance society’s capability to understand, anticipate, and respond to climate variability and change.
manage the impacts of seasonal climate fluctuations, in order to improve human welfare and the environment, especially in developing countries. This mission is to be conducted through strategic and applied research, education and capacity building, and provision of forecast and information products, with an emphasis on practical and verifiable utility and partnerships.

Langmuir Center for Colloids and Interfacial Spectroscopy. The center brings together experts from mineral engineering, applied chemistry, chemical engineering, geosciences, and chemistry to probe complex interactions of colloids and interfaces with surfaces, biomolecules. LCIS activities involve significant interaction with industrial sponsors and adopt an interdisciplinary approach toward the state-of-the-art research on interfacial phenomena. Major areas of research at LCIS are thin films, surfactant and polymer adsorption, environmental problems, enhanced oil recovery, computer tomography, corrosion and catalysis, petroleum reservoirs, nanotechnology, novel separations of surfactants and macromolecules. LCIS activities are tightly coupled. Fossil fuel resources—CO2 emission and water usage—are important for the significant reduction of energy consumption, and federal agencies responsible for climate change issues impact the design and operation, as well as the associated environmental, health, and safety concerns. The LCIS graduate students are specially trained in the following areas of focus within the department.

The first two years of the EEE program are similar to those of other engineering programs. Students are strongly encouraged to work as summer interns in industry or agencies on projects related to Earth and Environmental Engineering. The department helps students get summer internships.

Graduate Programs

M.S. students must complete the professional development and leadership requirements, ENGI E4000, as a graduation requirement. Ph.D. candidates are strongly encouraged to complete ENGI E6001-6004 and should consult their program for 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 and development careers. The focus of the program is the production, processing of primary materials (minerals, energy, water) and the recycling or proper disposal of used materials. The program also includes technologies for assessment and remediation of past damage to the environment. Students can choose a pace that allows them to complete the M.S.-EEE requirements while employed. M.S.-EEE graduates are specially qualified to work for engineering, financial, and consulting firms engaged in mineral processing ventures, the environmental industry, environmental groups in all industries, and for city, state, and federal agencies. In addition, 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 resources systems, and related sectors such as energy, health, agriculture, ecological resources, and natural hazards control. Climate uncertainties can be broadly classified into two areas: (1) those related to interannual climate variability and predictability, and (2) those related to seasonal to century-scale variations. The climate change impacts to water resources systems are due to physical, social, and financial infrastructure systems to support the sector, as well as to the sectoral variability, and climate risk is to provide a (1) a capacity for understanding and quantifying the projections for climate change 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. Specific areas of interest include:

- Numerical and statistical modeling of global and regional climate systems and attendant uncertainties
- Methods for forecasting seasonal to interannual climate variations and their sectoral impacts
- Models for design and operation of water systems affected by riparian, agricultural, climate and other uncertainties
- Integrated risk assessment and management across water resources and related sectors

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 this program is to develop advanced technologies and infrastructures and to bring together experts from mineral engineering, electrical engineering, and environmental engineering to develop effective strategies for sustainable energy concentration is one of the central tasks for modern engineering. The purpose of this program is to develop advanced technologies and infrastructures and to bring together experts from mineral engineering, electrical engineering, and environmental engineering to develop effective strategies for sustainable energy. The interdisciplinary nature of the program is evidenced by the teaching faculty, which include:

• Civil Engineering, Chemical Engineering, Mechanical Engineering, and Earth and Environmental Engineering (Lamont-Doherty Earth Observatory), as well as the Malin School of Public Health, computer science, and engineering.

For students with a B.S. in engineering, at least 90 credit courses are required. For students with a nonengineering B.S. or a B.A., preferably with a science major, up to 140 credit courses (total of sixteen courses) may be required for makeup courses. Students may carry out a research project and write a thesis or project paper. A number of areas of study are available for the M.S.-EEE, and students may choose courses that match their educational and career plans. The areas include:

- Alternative energy and carbon management
- Climate risk assessment and management
- Environmental health engineering
- Sustainable waste management
- Natural and mineral resource development and management
- Novel technologies: surficial and colloidal chemistry and nanotechnology
- Urban environments and spatial analysis
- Water resource systems and management
- Drinking water purification, desalination and wastewater treatment

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, and details and the lists of specific courses for each track are available in the department.

Students interested in a specific focus in Mining Engineering or related fields should consult their faculty adviser for relevant course listings.
Sustainable Mining and Materials

Earth mineral and metal resources are finite and central to the economy and industrialization. The interactions of human and 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 science and sustainability are another aspect of the concentration. Additional specialization may consider region-specific energy development.

M.S. in Carbon Management

Interdisciplinary training with a core curriculum in engineering, ecology, decision science, business, and law. The program is designed for engineers who wish to work after advanced work in the level of the M.S. degree but who do not wish it to be an additional degree. Admissions requirements include Undergraduate engineering in these, 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. The course will cover the following topics in their development during the first two semesters. The required coursework includes four core classes and six elective courses from a pre-approved list of choices. Core courses:

- EAEE E4101 Industrial ecology of earth resources
- EAEE E4000 Geographic information systems (GIS) for resource, environment, and infrastructure management
- EAEE E4060 Field methods for environmental engineering

Elective courses may include 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 advisor. The following are required courses and processes with the transformational innovations under development in the Earth resources management sector.

Concentration-specific classes will sketch out the availability of resources, their geographic distribution, the economic and environmental cost of transformational innovations, and 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, wind, energy storage; and technological and policy issues. Most classes focus on 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 science and sustainability are another aspect of the concentration. Additional specialization may consider region-specific energy development.

Doctoral Problems

The engineering objectives of EEE and its interactions with environmental concerns are 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, management of industrial residues, 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 program in Sustainable Mining and Materials integrates the fundamentals of environmental engineering and processes with the transformational innovations under development in the Earth resources management sector.

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Prerequisite: CHEM UN1404 or equivalent. Fundamentals of microbiology, genetics and molecular biology, principles of microbial nutrition, energetics and kinetics, application of novel and clean technologies, laws, regulations, and clean technologies, laws, regulations, and guidelines. Examples of industrial and environmental applications illustrated by means of laboratory experiments. Statistical methods include regression, analysis of variance, design of environmental and environmental applications. Examples of industrial and environmental applications illustrated by means of laboratory experiments. Statistical methods include regression, analysis of variance, design of experiments, and models. Laboratory emphasis on the principles underlying water analysis of specific projects for flood mitigation, urban design, and emergency response to natural or man-made disasters. U.S.-international case studies on topics ranging from water and wastewater treatment, or distribution and use, interpolation and visualization of spatial factors. New York City and other standard databases. Term projects emphasize information synthesis and presentation of results among related disciplines. Thermochemistry, thermodynamic, and chemical kinetics. Principles of multistaged operations for solid and hazardous waste treatment, and for the production of inorganic salts; electrolytic treatment of wastes; primary, secondary, and fuel cells.

ECIA W4100y Management and development of water systems 3 pts. Lect: 3. Professor Yin. Decision analysis framework for operating, managing, and planning water systems. Physical and chemical properties of solid and liquid fuels. Laboratory emphasis on the principles underlying water analysis of specific projects for flood mitigation, urban design, and emergency response to natural or man-made disasters. U.S.-international case studies on topics ranging from water and wastewater treatment, or distribution and use, interpolation and visualization of spatial factors. New York City and other standard databases. Term projects emphasize information synthesis and presentation of results among related disciplines. Thermochemistry, thermodynamic, and chemical kinetics. Principles of multistaged operations for solid and hazardous waste treatment, and for the production of inorganic salts; electrolytic treatment of wastes; primary, secondary, and fuel cells.

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EAEI 4190s Photovoltaic systems
engineering and sustainability 3 pts. Lect. Not offered in 2020–2021. Prerequisite: Senior standing or instructor’s permission. A systems approach for intermittent renewable energy involving the photovoltaic devices, generation, demand, storage, transmission, economics and politics. Study of emerging photovoltaic technologies, with focus on basic sustainability metrics (e.g., cost, resource availability, life-cycle characteristics). The status and potential of first- and second-generation photovoltaic technologies (e.g., crystalline silicon, CdTe, C60) and emerging third-generation ones. St Strategies to overcome the intermittency constraint. Large scales of renewable energy technologies and plug in hybrid electric cars.

EAEI 4240y Introduction to sustainable productivity of major and metal resources 3 pts. Lect. Professor Fanous and Flanagan. Prerequisite: ENME E3161 or MSAE E3161. Undergraduate level courses in chemistry (especially inorganic, physical, and organic). Introductory course focused on engineering principles and units and operations involved in sustainable processing of primary and secondary minerals and metals. Covers core value chain, viz., aspects of economic resource deposits, mining, fundamental industrial processes of flotation, precipitations. Emphasis on concepts in interfacial transport, magnetic/gravity/ centrifugal separation science and engineering principles of important solid-liquid and liquid-liquid separations used in processing of mineral resources. Interfacial quality and treatment, air pollution emissions, addressing environmental problems such as water and energy efficiency and management, and legal and regulatory framework, environmental engineers and government agencies, including engineering applications for 'mines of the future' framework. Highlight innovations and transformative sustainable mining technologies. Covers wide range of solid, liquid-solid and liquid-liquid separations used for processing of mineral resources. Inorganic science and engineering principles of important industrial processes of flotation, filtration, absorption, drying, intermetallic, transport, and chemical/ electrochemical separations, solvent extraction, solid-state separation, crystallization, precipitation. Emphasis on concepts in interfacial chemistry and concepts associated with 'mines of the future' framework.

EAEI 4252y Separation science and technology in sustainable earth resources development 3 pts. Lect. Professor Chandran. Prerequisite: CHEM UN3401 or equivalent. EMME E3161 or equivalent. Engineering aspects of problems involving interaction with the natural environment: conceptual, fundamental 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 for processing of mineral resources. Inorganic science and engineering principles of important industrial processes of flotation, filtration, absorption, drying, intermetallic, transport, and chemical/ electrochemical separations, solvent extraction, solid-state separation, crystallization, precipitation. Emphasis on concepts in interfacial chemistry and concepts associated with 'mines of the future' framework.

EAEI 4252x Separation processes involving particulates and powders 3 pts. Not offered in 2020–2021. Prerequisite: CEEI E3101 or equivalent. Course topics include the fundamental theory of electrochemical corrosion, corrosion mechanisms, and applications of metal protection. Emphasis is given to effective planning and management of urban hydrologic systems.

EAEI 4255x Groundwater contaminant characterization and breakout groups, student presentations, and class debates and breakout groups, student presentations, and class debates and breakout groups.

ECE 4520x Groundwater contaminant transport and remediation 3 pts. Not offered in 2020–2021. Prerequisites: CHEM E3101 or equivalent. The course is focused on the study of the chemical and fundamental principles underlying the development of geologic, engineering, and economic aspects of greenhouse gas emissions and their impact on energy security, economic development and climate change. The course is designed to provide students with an understanding of greenhouse gas emissions, the impacts of each technology, full spectrum of economic, environmental, regulatory, and political aspects, and their implications for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

ECE 4520x Environmental data and monitoring technologies to store carbon dioxide, geological, or biological systems. Conversion of CO2 to chemical and fuels, and other methods. Applications to capture carbon dioxide via new or existing technologies to store carbon dioxide, geological, or biological systems. Conversion of CO2 to chemical and fuels, and other methods. Applications to capture carbon dioxide via new or existing technologies.

ECE 4525x Groundwater contaminant characterization and breakout groups, student presentations, and class debates and breakout groups.

ECE 4526x Environmental data and monitoring technologies to store carbon dioxide, geological, or biological systems. Conversion of CO2 to chemical and fuels, and other methods. Applications to capture carbon dioxide via new or existing technologies to store carbon dioxide, geological, or biological systems. Conversion of CO2 to chemical and fuels, and other methods. Applications to capture carbon dioxide via new or existing technologies.
EAEE E4901 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 microbially mediated processes; biotechnology and engineering applications using microbial systems for pollution control.


EAEE E4905 Engineering systems for water treatment and reuse 3 pts. Lect: 3. Professor Chandran. Offered in 2020–2021. Prerequisites: CIEE E4163 and EAEE E3001, or the instructor’s permission. Application of fundamental principles to designing water treatment and reuse systems. Development of process designs for a potable water treatment plant, a biological wastewater treatment plant, or a water reclamation and reuse facility by students working in teams. Student work in evaluation of water quality and pilot plant data, screening process alternatives, conducting regulatory reviews and research, and reports for implementation and support by engineering drawings and capital operating costs. Periodic oral progress reports and a full engineering report are required. Presentations by practicing engineers, utility personnel, and regulatory and field trips to water, wastewater, and waste reuse facilities.


EAEE E4990y and y Fieldwork 1 pt. Members of faculty. Prerequisites: Instructor’s written permission. Only EAEE graduate students who read relevant campus work experience as part of their program of study as determined by the instructor. Written reports and class application must be made prior to registration and outlining proposed study program. Final reports are 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.

EAEE E6132y Numerical methods in geomechanics 4 pts. Lect: 3. Professor Chen. Prerequisites: EAEE E3112 and CIEE 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 strain and loading on the surface and underground.

EAEE E6146 Environmental physical processes 3 pts. Lect: 3. Professor Yip. Prerequisites: CIEE E4325 and CIEE E4163 or the equivalent, or the instructor’s permission. Fundamentals and applications of key physical processes relevant to water quality engineering (such as water treatment, wastewater treatment/reuse, recycling, desalination) and the natural environment (e.g., lakes, rivers, groundwater).

EAEE E6159y Industrial catalysis 3 pts. Lect: 3. Professor Farrauto. Prerequisite: EAEE E4505 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 catalysis, focusing on advanced catalytic applications as described in modern literature and patents.


EAEE E6161y Advanced electrochemical energy storage 3 pts. Lect: 3. Professor Sigantor. Prerequisites: EAEE E4180, E4002. Most modern implementations of commercial energy storage devices are not fully deterministic; provides context and best- current methods for modeling. Topics include: current understanding of lithium/lithium anode solid-electrolyte interphase, reversible uptake and intercalation of lithium in positive electrode materials. Electrochemical processes at multiple scales, relationships between electrode voltages and electrode insertion, roughening, smoothing, and detachment behavior of metal anodes, best practices in structural, chemical, and microscopic characterization, morphological, e.g., macro-homogeneous transport models, particle-to-electrode to cell-landing.

EAEE E9250x and y Complexity science 4 pts. Lect: 4. Professors Caster, Dumais, Lafl, Marc Rives. Prerequisites: Graduate standing and instructor’s permission. Survey of theories, applications, and implications of complex systems science and complex systems. Topics include systems dynamics, chaos, scaling, fat-tailed distributions, fractals, information theory, emergence, critically, agent-based models, graph theory, and social networks. Applications in complex biological systems, hydrology, geophysics, physics, social theory, epidemiology, and governance.

EAEE E9252y Carbon footprint determination 3 pts. Lect: 3. Professor Park. Prerequisite: EAEE E3204 or equivalent in electrical/electronics engineering. New techniques for capturing carbon dioxide and disposing of it away from the atmosphere. Detailed discussion of the extent of the human footprint on the natural carbon cycle, the motivation and scope of future carbon management strategies and the role of carbon sequestration. Introduction of several carbon sequestration technologies that allow for the capture and permanent disposal for carbon dioxide. Engineering issues in their implementation, economic impacts, and the environmental issues raised by the various methods.

CHEE E6252y Advanced physical chemistry 3 pts. Lect: 4. Professors Samuelsen and Farnese. Prerequisite: CHEE E4024. Applications of surface chemistry principles to wetting, fluidization, filtration, separation techniques, catalysis, mass transfer, simulations, trains, aerodynamics, membranes, biological surfactant systems, microbial surfaces, enhanced oil recovery, and pollution problems. Appropriate individual experiments and projects.

CHEE E6265x and y Methods and applications of analytical decision making in mineral industries 3 pts. Lect: 3. Not offered in 2020–2021. Prerequisites: Instructor’s permission. Advanced study of decision-making problems with critical survey and analysis of quantitative decision-making techniques in mineral industries. Systematic development of the methodologies of the formulation, analysis, and resolution of these problems.

CHEE E6326y and y Water, sanitation, and human health 3 pts. Lect: 3. Professor Shaman. Prerequisite: Instructor’s permission. In-depth analysis of issues relating to water, sanitation, and hygiene in both the developed and developing worlds. Effects of water cyclic science, biogeochemistry, public health, water resources, hydrology, geophysics, physics, social theory, epidemiology, and governance.


EAEE E6184x and y Advanced electrochemistry and electrocatalysis 3 pts. Lect: 3. Instructor to be announced. Prerequisites: CHEE E4003 and CHEE E4030, or instructor’s permission. Review of current research and literature in the field of hydrometallurgy, electrochemistry, and corrosion. Topics will be selected by the instructor to illustrate the application of thermodynamics and rate phenomena to this class of electrochemically engineering processes.

EAEE E8231x and y Research topics in particle processing 3 pts. Professor Samuelsen. Emergent findings in the interactions of particles with microsensors and solutions, especially microarrays, surfactants, and polymers in solutions, and their role in guiding, flotation, agglomeration, filtration, enhanced oil recovery, and other mineral processing operations.


EAEE E8271x and y-95271 Earth and environmental engineering thesis D-pts. Members of the faculty. Research work culminating in a credible 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 distinct character is required in its handling.

EAEE E8273x and yEarth and environmental engineering reports 3-4 pts. May substitute for formal thesis, EAEE E8701, upon recommendation of the department.

EAEE E9260x and y Earth and environmental engineering colloquium 3 pts. Lect: 1.5. Professor Yip. All graduate students are required to attend the departmental colloquium as long as they are in residence. Advanced doctoral candidates are required to attend the colloquium until the degree has been awarded.

EAEE E9305x and y Doctoral research 3, 6, 9, or 12 pts. Members of the faculty. Graduate research directed toward solution of a problem in mineral processing or chemical metallurgy.
The need for increasingly faster and more powerful devices, systems, and network concepts and analytical tools of undergraduate program in electrical engineering has led to the continued development of new innovations through its program of academic instruction and research. The undergraduate program in electrical engineering is designed to prepare students for a career in industry, research, or business by providing them with a strong foundation in the fields of signals and data.}

**Laboratory Facilities**

Current research activities are fully supported by the well-equipped research laboratories run by the department faculty. In addition, faculty members 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 Science Systems Laboratory, Structure-Function Imaging Laboratory, Neural Acoustic Processing Laboratory, Signal Processing and Communication Laboratory, Translational Neuroelectronics Laboratory, Biofilm Laboratory, Molecular Beam Epitaxy Laboratory, Surface Analysis Laboratory, and Laboratory for Unconventional Electronics, Advanced Semiconductor Devices Laboratory, Motor Drives and Power Electronics Laboratory, Intelligent and Connected Systems Laboratory, Columbia Integrated Systems Laboratory (CISL), Applied Physics and Applied Mathematics Laboratory, MJSi Design Laboratory, High Speed and mmWave IC Laboratory, Analog and Mixed-signal Circuit Design Laboratory, Lightwave Laboratory, and Nano Photonics Laboratory.

Laboratory instruction is provided in a suite of newly-rewritten facilities on the twelfth floor of the S. W. Mudd Building. These teaching laboratories are used for circuit prototyping, device measurement, MJSi design, embedded systems design, as well as computer engineering and Internet-of-Things experiments.

**Electrical Engineering**

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:

A. Graduate or professional studies—as evidenced by admission to a top-tier program, attainment of advanced degrees, research contributions, or professional recognition.

B. Engineering practice—as evidenced by entrepreneurship; employment in industry; and activity in nonprofit organizations in engineering; patents; or professional recognition.

C. Professional studies—as evidenced by admission to a top-tier professional program, attendance of advanced degrees, research contributions, or professional recognition. For all students, irrespective of their major emphasis, these courses will take advantage of an engineering education—as evidenced by contributions appropriate to the chosen field.

The Electrical Engineering program will prepare 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, and environmental factors.

The Electrical Engineering program is designed with the following:

E. Ability to understand and analyze biological systems within the living cell and in the environment, develop computer interfaces, and biological models for data analysis, synthetic biology, and proteomics.

F. Ability to conduct research under faculty supervision at which the leading edge of technology and applied science are offered in all research areas.

G. The Electrical Engineering program, 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.
### ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

#### EARLY-STARTING STUDENTS

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<th>SEMESTER I</th>
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#### MATHEMATICS
- APMA E2000 (4) either semester
- APMA E2101 (3)1

#### PHYSICS (three tracks, choose one)
- UN101 (3)
- UN102 (3)
- UN110 (4)
- UN111 (4)

#### CHEMISTRY
- one-semester lecture (3–4)
- UN1103 or UN1104 or UN1105

#### CORE REQUIRED COURSES
- ELEN E1201 (3.5) Introduction to electrical engineering (either semester)
- ELEN E3001 (3.5) Circuit analysis
- ELEN E3011 (3.5) Signals and systems
- ELEN E3311 (3) Electronic circuits
- ELEN E3321 (3) Fundamentals of computer systems

#### REQUIRED LABS
- ELEN E2001 (1)*
- Signals and systems lab
- ELEN E2002 (1)*
- Digital systems lab

#### UNIVERSITY WRITING
- CC1010 (3) either semester

#### REQUIRED NONTECHNICAL ELECTIVES
- HUMA CC1101, CCID CC1101, or Global Core (3–4); HUMA UN1121 or UN1123 (3); HUMA CC1200, CCID CC1102, or Global Core (3–4); ECON UN105 (1) and UN1115 (1) (or equivalent, 5)

#### COMPUTER SCIENCE
- ENGI E1006 (2) either semester2

#### PHYSICAL EDUCATION
- UN101 (1)
- UN102 (1)

#### THE ART OF ENGINEERING
- ENGI E1102 (4) either semester

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1. APMA E2101 may be replaced by MATH UN2030 (formerly MATH E1210) and another APMA E3101 or MATH UN3110.
2. 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

#### EARLY-STARTING STUDENTS

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#### PHYSICS (tracks continued)
- Lab UN1494 (3)*
- Lab UN2699 (3)
- Lab W3081 (2)

#### EE CORE REQUIRED COURSES
- ELEN E3101 (3) Electromagnetics
- ELEN E3701 (3) Intro. to communication systems or CSEE W4119 (3) Computer networks

#### EE REQUIRED LABS
- ELEN E3106 (3.5) Solid-state devices and materials

#### OTHER REQUIRED COURSES
- EE DEPT.
- BREADTH
- OTHER
- NONTech

#### TECH
- ELEN E3403 (3) Solid state, microwave, and fiber optics lab
- ELEN E3599 (1) EE project
- ELEN E3990 (3)* Capstone design course

#### ELECTIVES
- 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

#### NONTech
- Complete 27-point requirement; see page 9 (27 Point Nontechnical Requirement) or see.columbia.edu for details (administered by the advising dean)

#### TOTAL POINTS
- 16.5
- 17
- 16
- 18

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1. Chemistry lab (CHEM UN1001) 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 "challenging 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 E3299, it is possible to use courses such as ELEN E3888, E4350, E4988, ECEC 4345, or CSEE W4840 in place of ELEN E3300.
4. ECON W3010 and STAT W2113 cannot generally be used to replace EIDE W3050 or STAT W2103.
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 UN3110. 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.

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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 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 and culture, philosophy, economics,
and enter other fields in which engineering is essential. 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 electrical 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

### ELECTRICAL ENGINEERING: THIRD AND FOURTH YEARS

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<tr>
<td>ELEN E3106 (3.5)</td>
<td>ELEN E301 (1.5)</td>
<td>CSEE W3672 (3)</td>
<td>ELEN E301 (1.5)</td>
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<tr>
<td>Solid-state devices and materials</td>
<td>Electronic circuits</td>
<td>Fund of computer sys.</td>
<td>Electromagnetics</td>
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<tr>
<td>ELEN E3200 (3.5)</td>
<td>ELEN E3401 (4)</td>
<td>ELEN E3331 (3)</td>
<td>ELEN E3701 (3)</td>
</tr>
<tr>
<td>Circuit analysis</td>
<td>Electromagnetics</td>
<td>Intro. to communication systems</td>
<td>Intro. to communication systems</td>
</tr>
<tr>
<td>ELEN E3301 (3.5)</td>
<td>ELEN E3410 (4)</td>
<td>ELEN E3801 (3)</td>
<td>ELEN E4119 (3)</td>
</tr>
<tr>
<td>Signals and systems</td>
<td>Electromagnetics</td>
<td>Digital circuits lab</td>
<td>Computer networks</td>
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<tr>
<td>Lab E1494 (2)</td>
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<td>ELEN E3038 (3)</td>
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<tr>
<td>University English</td>
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<td>Solid-state, microwave, and fiber optics lab</td>
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<td>ELEN E3039 (1)</td>
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<td>ELEN E3043 (3)</td>
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<td>EE practice</td>
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<td>ELEN E3500 (3)</td>
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<td>ELEN E3500 (3)</td>
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<td>Capstone design course</td>
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### OTHER REQUIRED COURSES

- IBDR E3658 or STAT GU4203
- COMPS W1130 or W3134 or W3137

(Some of these courses are offered in both semesters)

### ELECTIVES

- At least 2 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.)

### BREATH TECH

- At least 6 points total

### OTHER TECH

- 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

### NONTECH

- Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement) or seas.columbia.edu for details (administered by the advising dean)

### TOTAL POINTS

- 15.5
- 18
- 16
- 18
The 18-point technical elective requirement for the engineering program is divided into two parts: breadth and depth. The breadth component consists of at least 6 additional points of courses that are outside of the chosen depth area and have significant engineering content. These courses must be taken for credit from different departments within the school. The breadth requirement encourages the exploration of engineering-related courses that complement the depth area chosen. Breadth also reduces the chances of obsolescence as technology changes. Any remaining technical elective courses, beyond the minimum 12 points of depth and breadth, do not have to be electrical 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 in the 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. Students should choose courses that do not overlap with courses used in the depth area, and thus do not allow taking electives in that area; thus, such students cannot choose circuits and electronics as a depth area. This plan is for students who have taken a core course equivalent to ELEN E1201 at their school of origin, including a laboratory component. See the bulletin for a complete list of approved pre-engineering programs and physics departments at four-year colleges offering such courses. Such students can start taking courses in engineering 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 the core course is essential for a number of other core courses. Sample programs for both Plan 1 and Plan 2 for 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 engineering courses in one of four defined areas: (a) photonics, solids-state devices, and magnetronics; (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 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 must be taken for credit from different departments within the school. The breadth requirement encourages the exploration of courses that are outside of the chosen depth area. The breadth component of the program includes a variety of courses that provide both breadth and depth in a specific area of interest. More detailed information about the breadth and depth requirements can be found in the Electrical Engineering home page at ee.columbia.edu.
Three courses from the following list (courses cannot be used to fulfill both this requirement and any of the above requirements): ELEN E4848: Optical interconnects and interconnection networks; ELEN E6761: Computer communication networks; ELEN E6767: Internet economics, energy, and society; ELEN E6770: Topo...

CSEE W4823x or Advanced Logic design 3 pts. Lect: 3. Professor Nowick. Prerequisite: CSEE W3827 or equivalent. An introduction to modern digital system design. Advanced topics in digital logic design (synthesis (Moore and Mealy machines), and flip-flop circuits, structural block diagrams (PLDs, PLAs, and logic gates). Introduction to Computer-Aided Design (CAD) for digital logic design. Modern computer-aided logical design techniques for hardware synthesis (VHDL or Verilog) and logic synthesis. Programmable logic devices (PLDs, FPGAs) and other programmable logic devices. Applications to circuits and devices, to communication, control, filtering, and prediction.
ELEN E4900x or y System-on-chip platforms 3 pts. J. Professor Trivino. Science and technology of conventional and SoC platforms for various classes of applications. Topics include design tools for VLSI, add-on microcontroller units, and power-supply noise. Computer-aided design tools for SoC. Recommended: ELEN E4810. Design and implementation of complex circuits using VHDL.
ELEN E3530y Semiconductor device physics
3 pts. Lect. 2.
Prerequisites: ELEN E3016 or ELEN E3410 or equivalent. Physics and properties of semiconductors. Transport and recombination of charge carriers, P-N, M-O-S, and heterojunction diodes. Field effect and bipolar junction transistors. Dielectric and optical characteristics of semiconductors. Semiconductor lamps, lasers, and detectors.

ELEN E3950y VLSI design laboratory 3 pts. Lect. 2.
Prerequisites: ELEN E3421 and E4312, or instructor’s permission. Design of a CMOS mixed-signal integrated circuit. The class divides into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be hosted 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 circuit design.

ELEN E4120y Lightwave devices 3 pts. Lect.; Professor Woodward.
Prerequisites: ELEN E4411. Electro-optics: principles, electro-optics of liquid crystals and photo-refractive materials. Nonlinear optics: second-order nonlinear optics; third-order nonlinear optics; optical limiting and switches. Acousto-optics: interaction of light and sound; diffraction, applications of acousto-optics in testing and computing; photonic switches; all-optical switches; bistable optical devices. Introduction to fiber communications, components of the fiber optic link; modulation, multiplexing and coupling; system performance; receiver/sender design and implementation.

ELEN E4140y Lightwave systems 3 pts. Lect.; Professor Fauer.
Prerequisites: ELEN E4411. Recommended preparation: ELEN E4411 or E4441. Introduction to optical interconnects and interconnection networks for fast parallel digital systems. Fundamental interoptical technologies, optical interconnection network design, characterization, and performance evaluation. Enabling photonic technologies including free-space structures, hybrid, and monolithic integration platforms for photonic chips, chip-to-chip, backbone, and node-to-node interconnections, as well as photonic networking on-chip.

EEME E6040a Introduction to control theory 3 pts. Lect.; Professor Liekang.
Prerequisite: 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 stability, proportional, rate, and integral, and compensators. Design by root locus and frequency response. Controllability of linear systems. Luembberger observers, pole placement, and linear quadratic controllers.

EEME E6040b Modern control theory 3 pts. Lect.
Prerequisites: EEME E6601 or E4601 or ELEN E6220, or instructor’s permission. Singular value decomposition. ARX model and state-space model identification. Recursive least squares filters and Kalman filters. LQR, linear quadratic control, predictive control. Linear quadratic regulator. Adaptive control. Luenberger observers and pole placement. LQR and Popov stability. Nominally adaptive control, nonlinear robust control, sliding mode control.


EECS E6630x or Topics in data-driven analysis and computation 3 pts. Lect.; Members of the faculty. Prerequisite: Instructor’s permission. Selected advanced topics in data-driven analysis and computation. Content varies from year to year, and different topics rotate through the courses E6600 to E6699.

ELEN E6711x Stochastic models in information and communication systems 3 pts. Lect.; Professor Raskhodnikov. Prerequisites: IESC E3658. Foundations of probabilistic models for random processes, stochastic models, stationary, 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: network communication systems (packet systems); biological systems (hidden Markov models); Bayesian restoration of images (Gibbs sampling) and wireless communications (Markov models).

ELEN E6712x Communication theory 3 pts. Lect.; Professor Easwar. Prerequisite: ELEN E4615, or equivalent, or permission of the instructor. Course covers some of the fundamental aspects of communication systems and associated models. An introduction to the theory of information and coding systems. Topics include Gaussian and non-Gaussian noise, fading channels, and communication over bandwidth limited channels. Prerequisite: ELEN E4612, or equivalent.

ELEN E6715x Topics in communication theory 3 pts. Lect.
Prerequisites: ELEN E6712 or E4702 or E4703 or equivalent, or instructor’s permission. Advanced topics in communications, such as turbo codes, LDPC codes, multiuser communications, network coding, cross-layer optimization, and cognitive radio. Content may vary from year to year to reflect the most development in this field.

ELEN E6717x Information theory 3 pts. Lect.; Professor Wang.
Prerequisites: ELEN E6001 or equivalent course in information theory. Prerequisite: ELEN E6001 or ELEN E4415. Mutual information and entropy. The source coding theorem. The capacity of discrete memoryless channels and the channel coding theorem. The rate distortion function. Discrete memoryless sources and single-letter distortion measures.

Bhattacharyya bounds, conditional codes, and the Viterbi algorithm.

ELEN E6718x Error correcting codes: classical and modern 3 pts. Lect.; Professor Ashikhmin.
Prerequisites: IESC E5656. Main concepts of error correction and codes. Block codes, cyclic codes, BCH codes, Reed Solomon codes. Convolutional Codes. Turbo codes. Low density parity check codes. Turbo codes and Polar codes.

EECS E6720x Bayesian models for machine learning 3 pts. Lect.; Professor Pasley. Prerequisite: Basic calculus, linear algebra, probability, and programming. Basic statistics and machine learning strongly recommended. Bayesian approaches to machine learning. Topics include maximum-likelihood, maximum a posteriori probability, Markov models, Gaussian models, and models based on mixture of latent variables and graphical models. Bayesian inference and learning. Applications include image processing, topic modeling, collaborative filtering, and recommendation systems.

ELEN E6761x Computer communication networks I 3 pts. Lect.; Professor Ghadiri. Prerequisites: IESC E5656 or equivalent, or instructor’s permission. Recommended: CSWE W4419. Analytical approach to the design of (data) communication networks. Necessary tools for performance analysis and design of network protocols. Analysis of traffic and congestion avoidance in layered internet protocol (IP) core networks. DSP and communications on network layer.

ELEN E6860y Speech and audio processing and recognition 3 pts. Lect.; Professor Mogiann. Prerequisite: Knowledge of programming, ELEN E4703 or related, or ELEN E4415 or instructor’s permission. Internet of Things from the point of view of computer science and electrical engineering. Understanding the internet of things and other connected systems. Students will learn how to understand machine learning techniques and how to use them in their personal and professional lives. Prerequisites include theory, and hands-on experience with computer science and electrical engineering.

ELEN E6861x Internet of Things—systems and data analytics 3 pts. Lect.; Professor Kostic.
Prerequisite: Knowledge of programming, ELEN E6717 or equivalent, or instructor’s permission. Internet of Things from the point of view of computer science and electrical engineering. Understanding the internet of things and other connected systems. Students will learn how to understand machine learning techniques and how to use them in their personal and professional lives. Prerequisites include theory, and hands-on experience with computer science and electrical engineering.

ECSW E6770x Computer-aided design of digital systems 3 pts. Lect.; Professor Nguyen. Prerequisite: ELEN E4415 or equivalent, or instructor’s permission. Course is designed as an extension to ELEN E4810, with emphasis on emerging techniques in the area of computer-aided design. Topics include multirate signal processing, multidimensional signal processing, short-time Fourier transform, signal processing for telecommunications, digital signal processing, filter banks, multiresolution analysis, wavelets, and their applications to image compression and understanding. Other topics may be included to reflect developments in the field.

EECS E6864x Computer-aided design of digital systems 3 pts. Lect.; Professor Nguyen. Prerequisites: (i) one semester of advanced digital systems (EECS W4423 or equivalent, or instructor’s permission); and (ii) a basic course in data structures and algorithms (COMS W3130, W3131, W3134, W3137, W3139 or W3157, or equivalent), and familiarity with programming. Introduction to modern digital CAD synthesis and verification techniques. Advanced topics in modern digital system design (high-level synthesis, register-transfer level modeling, algorithm-based statistics, optimization, scheduling, decision-making, and system synthesis).
Course: ELEN E8617x or y Sparsity and low-dimensional models for high-dimensional data analysis. This course covers the theory and practice of compressed sensing, optimization techniques, and low-dimensional models. Prerequisites: ELEN E4614 or equivalent.

Course: ELEN E6800/6810x and y Topics in signal processing. This course covers advanced topics in signal processing, including multichannel 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 6800 to 6819.

Course: EELS E6860x or y Electrical engineering. This course provides an understanding of the methods used for filtering, modeling, and analysis of linear and non-linear circuits and systems, covering topics such as Fourier analysis, Laplace transforms, and state-space methods. Prerequisites: ELEN E3331 and APMA E3101.

Course: ELEN E6875x Wireless and mobile networking, I. This course covers topics such as wireless communication systems, wireless ad-hoc and sensor networks, and energy-efficient design of wireless systems. Prerequisites: ELEN E6811 or instructor's permission.

Course: ELEN E6810y or y Analog design. This course covers advanced analog design topics, including MOSFET and BJT transistors, power amplifiers, and linear integrated circuits. Prerequisites: ELEN E3331 and ELEN E3801.

Course: ELEN E6900y or y Electrical engineering. This course covers advanced topics in computer engineering and scientific computing, such as image and multimedia content analysis, and other areas including signal processing, inverse problems, machine learning, pattern recognition, and related topics. Content varies from year to year, and different topics rotate through the course numbers 6800 to 6819.

Course: ELEN E6900-6909x or y Topics in optical communications. This course covers advanced topics in optical communications, including fiber optics, optical amplifiers, and optical modulation and detection. Prerequisites: ELEN E3331 and ELEN E3801.

Course: ELEN E6910y or y Technical writing and presentation for engineers. This course covers topics such as technical writing, oral presentation, and academic publishing. Prerequisites: ELEN E1000 or equivalent.

Course: ELEN E8610y or y Doctoral research. This course provides an opportunity for doctoral students to conduct research in a topic of their choice. Prerequisites: ELEN E3101 and E4614, or equivalents. Recommended: ELEN E4614. This course provides an opportunity for students to conduct research in a topic of their choice. Prerequisites: ELEN E4614 or equivalent.

Course: ELEN E9900x or y Electrical engineering. This course covers advanced topics in electrical engineering, including advanced circuit theory, digital signal processing, and power electronics. Prerequisites: ELEN E3331 and APMA E3101.

Course: ELEN E8615x or y Ph.D. seminar. This course provides an opportunity for students to present their research in a seminar format. Prerequisites: ELEN E3331 and APMA E3101, or equivalents.
differential equations, companion network models; waveform relaxation.

**ELEN E6304x or y Topics in electronic circuits**  
3 pts. Lect: 3.  
Prerequisite: Instructor’s permission. State-of-the-art techniques in integrated circuits. Topics may change from year to year.

**EEEM E6610x Optimal control theory**  
3 pts. Lect: 3.  
Prerequisite: ELEN E6201 or EEME E6601.  

**ELEN E6762y Computer communication networks, II**  
3 pts. Lect: 2.  
Prerequisite: 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: admission and access control, flow control. ATM switch architectures; input/output queueing. Quality of service (QoS) concepts.

**ELEN E6781y Topics in modeling and analysis of random phenomena**  
3 pts. Lect: 3.  
Prerequisite: ELEN E6711. Recommended preparation: a course on real analysis and advanced probability theory. Current methodology in research in stochastic processes applied to communication, control, and signal processing. Topics vary from year to year and reflect student interest and current developments in the field.

**ELEN E6920x or y Topics in VLSI systems design**  
3 pts. Lect: 2.  

**ELEN E9060x or y Seminar in systems biology**  
3 pts. Lect: 2.  
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s permission. Study of recent developments in the field of systems biology.

**EEBM E9070x or y Seminar in computational neuroscience and neuroengineering**  
3 pts. Lect: 2.  
Professor Mesgarani.  
Open to doctoral candidates and qualified M.S. candidates with instructor’s permission. Study of recent developments in computational neuroscience and neuroengineering.

**ELEN E9101x or y Seminar in physical electronics**  
3 pts. Lect: 2.  
Prerequisites: Quantum electronics and ELEN E4944, or instructor’s permission. Advanced topics in classical and quantum phenomena that are based on ion and electron beams, gas discharges, and related excitation sources. Application to new laser sources and microelectronic fabrication.

**ELEN E9201x or y Seminar in circuit theory**  
3 pts. Lect: 2.  
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s permission. Study of recent developments in linear, nonlinear, and distributed circuit theory and analysis techniques important to the design of very large scale integrated circuits.

**ELEN E9301x or y Seminar in electronic devices**  
3 pts. Lect: 2.  
Professor Kymissis.  
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s permission. Theoretical and experimental studies of semiconductor physics, devices, and technology.

**ELEN E9303x or y Seminar in electronic circuits**  
3 pts. Lect: 2.  
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s permission. Study of recent developments in electronic circuits.

**ELEN E9402x or y Seminar in quantum electronics**  
3 pts. Lect: 2.  
Open to doctoral candidates, and to qualified M.S. candidates with instructor’s permission. Recent experimental and theoretical developments in various areas of quantum electronics research. Examples of topics that may be treated include novel nonlinear optics, lasers, transient phenomena, and detectors.

**ELEN E9403x or y Seminar in photonics**  
3 pts. Lect: 2.  
Prerequisite: 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 developments in theory and applications of signal processing, machine learning, content analysis, and related topics.

**EECS E9501x or y Seminar in electrical power networks**  
3 pts. Lect: 2.  
Prerequisites: 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.  
Instructor to be announced.  
Prerequisite: 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. Professor Jiang.  
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 areas 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, combinational 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 management, 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 Financial Engineering (CFE) 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.

Graduates prepare 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.
2 12 points total. At least two technical electives must be chosen from IEOR; the complete list is available at ieor.columbia.edu.

The department encourages students to select sequence 1 or 2. ENGI E1006 (3)

Taking required courses later than the prescribed semester is not permitted.

The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101.

COMS W3136 (3) may be substituted in place of sequence 1 or 2.

CC1010 (3) either semester

UNIVERSITY WRITING

FIRST- AND SECOND-ELECTIVES

(choose one course)

TOTAL POINTS

12 14 15 15

MATHEMATICS

MATH UN1101 (3) MATH UN1102 (3) APMA E2000 (4) Linear algebra (3)

ENGI E1102 (4) either semester

REQUIRED COURSES 1

(choose one)

UN 1401 (1) or UN 1402 (1)

UN1601 (3.5) or UN1602 (3.5)

UN1401 (3)

UN1402 (3)

UN1403 (3)

UN1404 (3)

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### OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: FIRST AND SECOND YEARS

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<tr>
<th>Semester</th>
<th>Mathematics</th>
<th>Physics</th>
<th>Chemistry</th>
<th>University Writing</th>
<th>Required NonTechnical Electives</th>
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<td>I</td>
<td>MATH UN1101 (3)</td>
<td>ENGI E1006 (3)</td>
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The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101.

* The department encourages students to select sequence 1 or 2. ENG S1102 (4) and COS W2110 (4) may be substituted in place of sequence 1 or 2.

### OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: THIRD AND FOURTH YEARS

<table>
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<th>Semester</th>
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* The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101.

* The department encourages students to select sequence 1 or 2. ENG S1102 (4) and COS W2110 (4) may be substituted in place of sequence 1 or 2.

### OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: THIRD AND FOURTH YEARS

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<td>ENGI E4000 (4)</td>
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<td>VI</td>
<td>MATH UN1102 (3)</td>
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<td>VII</td>
<td>APMA E2000 (4)</td>
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<td>18</td>
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* The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101.

* The department encourages students to select sequence 1 or 2. ENG S1102 (4) and COS W2110 (4) may be substituted in place of sequence 1 or 2.
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, 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 professional 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 inventory management in manufacturing firms, and fill quantitative roles in corporate sales and fill quantitative roles in corporate finance, sales, and marketing.

Undergraduate Advanced Track

The undergraduate advanced track is designed for advanced undergraduate students with the desire to pursue higher education in engineering. Engineering students are required to take the following courses, including the following:
- IEOR E4004 instead of IEOR E3692
- IEOR E4106 instead of IEOR E3106
- IEOR E4403 instead of IEOR E4003
- IEOR E4404 instead of IEOR E4340 and MATH UN2001

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 academic record. These minors are described starting on page 204 of this bulletin.

IEOR program students may want to consider minors in economics or computer science. In addition, the IEOR program 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. Ph.D. students are strongly encouraged to complete ENGI E3001–E4004 and should consult their program for 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 are offered in conjunction with the Columbia Graduate School of Business. Lastly, the Department and the Graduate School of Business 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 (or its equivalent in an undergraduate engineering program) is required for admission to the M.S. programs. At a minimum, students are expected 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 inadequacy of preparation and is very likely to lead to serious problems in completing the program. As a result, students failing to meet this criterion may be asked to withdraw.

Courses taken at the School of Professional Studies will not be counted toward the M.S. degree in the IEOR Department, as they do not have the appropriate rubrics with the following prefixes: ACTU, BUSI, COFR, IINS, SUMA, FUND, and more. Students are encouraged to consult with your academic adviser regarding electives offered in other departments and schools, prior to registration.

Business Analytics

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 recommendations with corporations, alumni, and students. It emphasizes on developing new insights and understanding of business performance using data, statistical and quantitative analysis, and explanatory and predictive modeling to help make actionable decisions and improve business operations. Students pursuing this degree program are provided with rigorous training in 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-designed program (equivalent of 12 three-credit courses), assuming adequate preparation in mathematics and statistics, with students taking at least six courses (18 credits) within the IEOR Department, and four to six courses (12–18 credits) at the Business School. The remaining courses, if any, can be taken at the School of Engineering, the School of International and Public Affairs, the Law School, or the Department of Economics, Mathematics, and Statistics. Additional details are available on the MSBA website: msba.engineering.columbia.edu/curriculum/content/program details.

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 EOR E4077, E4701, E4703, E4706, E4707, and E4709. In addition, students are required to attend IEOR E4706 Financial Engineering Seminar and submit learning journals.

Additional Financial Engineering electives will be offered 3

### Required Core Courses
1. **EOR E4077: Mathematical Finance**
2. **EOR E4701: Derivatives**
3. **EOR E4702: Stochastic Processes**
4. **EOR E4703: Financial Engineering**
5. **EOR E4706: IEOR600**
6. **EOR E4708: Numerical Optimization**

### Elective Courses
1. **EOR E4710: Managing Technological Innovation and Entrepreneurship**
2. **EOR E4711: Global Business**
4. **EOR E4713: Supply Chain Analysis**

### Additional Electives
1. **EOR E4714: Quality and Risk Management**
2. **EOR E4715: Data Science and Analytics**
3. **EOR E4716: Big Data and Analytics**
4. **EOR E4717: Network Analysis**
5. **EOR E4718: Supply Chain Management**

### Concentrations
1. **Operations Engineering (Operations Research)**
2. **Information Systems and Technology**
3. **Management Science**
4. **Quantitative Risk Management**

### Additional Requirements
1. **At least 18 points of graduate study**
2. **At least 12 points from the required core courses**
3. **At least 6 points from elective courses**

### Other Requirements
1. **Students must take at least six courses (18 points) within the EOR 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 O.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 coursework at Columbia.

### 3-point courses
1. **EOR E4040: Optimization models and methods (first fall semester)**
2. **EOR E4041: Probability, statistics, and simulation (first fall semester)**
3. **EOR E4400: Stochastic models (spring semester)**
4. **EOR E4411: Operations consulting (starts first fall semester, year-long course)**

### 5-point courses
1. **EOR E4400: Optimization models and methods (first fall semester)**
2. **EOR E4041: Probability, statistics, and simulation (first fall semester)**

### Topical Areas
- **Financial Engineering (12 points)**
- **Operations Research and Management Science (18 points)**

### In addition to the core and required courses, Management Science and Engineering (MS&E), offered by the EOR Department, has two main concentrations: (1) Healthcare and Biomedical Engineering and (2) Management Science. 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 required courses, Management Science and Engineering has six courses (12 points):

### Management Science and Engineering (36 points)

### Required Core Courses
1. **EOR E4040: Optimization models and methods (first fall semester)**
2. **EOR E4041: Probability, statistics, and simulation (first fall semester)**

### Elective Courses
1. **EOR E4400: Stochastic models (spring semester)**
2. **EOR E4411: Operations consulting (starts first fall semester, year-long course)**

### Concentrations
1. **Healthcare and Biomedical Engineering**
2. **Management Science**
3. **Quantitative Risk Management**

### Additional Requirements
1. **At least 18 points of graduate study**
2. **At least 12 points from the required core courses**
3. **At least 6 points from elective courses**

### Other Requirements
1. **Students must take at least six courses (18 points) within the EOR 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.**

### Operations Research
Graduate studies in Operations Research enables students to pursue specialized studies in methodological areas such as mathematical programming, stochastic
Students may complete the studies on a full-time (12 points per term) or part-time basis.

The requirements for the joint degree include a number of concentrations, including:

1. Analytics
2. Decision, Risk, and Analytics
3. Entrepreneurship and Innovation
4. Finance and Management
5. Healthcare Management
6. Logistics and Supply Chain Management
7. Machine Learning and Artificial Intelligence
8. Optimization

Students may select from a variety of approved electives from the Department of Columbia Business School, the School of Business, and the Graduate School of Arts and Sciences. Additional details regarding required courses and electives are available in the Department office and on IOR’s website: iocolumbia.edu.

JOINT M.S. AND M.B.A.

The department and the Graduate School of Business offer a joint M.S. and M.B.A. degree in Industrial Engineering. Prospective students for this special program must submit separate applications to Columbia Engineering and the Graduate School of Business 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 M.B.A. This joint program is coordinated so that both degrees can be obtained after five full-time study terms (30 points in two terms while registered in Columbia Engineering and 45 points in three terms while registered in the Graduate School of Business).

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 adviser in order to obtain exemption from a required course.

PH.D. PROGRAM

The IOR 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, and present it in defense 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 the original research, and present in it a department seminar at the beginning of the third semester; and
3. Submit a research paper in a journal during 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) and (2) will typically move on to summer research, advised by a faculty member in the third semester. If the student successfully completes component (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 (EOR 6110) do not count towards 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 must be obtained in the Department office and on IOR’s website: iocolumbia.edu.

COURSES IN INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

For up-to-date course offerings, please visit iocolumbia.edu.

EOR E2261x and y Accounting and Finance 3 pts.

Prerequisites: ECON UN1011 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 accounting; recognizing and measuring accounting transactions; preparing and analyzing financial statements; ratio analysis; pro-forma statements; time value of money; present value; future value; concept of inflation; discounted-cash flow (DCF) project evaluation methods; deterministic and probabilistic measures of risk; capital budgeting.

EOR E2263x and Stat GU4001 and knowledge of a programming language such as Python, C, C++ or Matlab. It is strongly advised that Probabilistic modeling courses (EOR 1106 or EOR 4106) 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 and exams always includes a programming component for which students are encouraged to work in teams.

EOR E3109y Foundations of optimization 3 pts.

Prerequisites: MATH UN3010. Concepts: Data structures. This first course in optimization focuses on theory and applications of linear optimization, network optimization, and dynamic programming.

EOR E3890 Advanced optimization 3 pts.

Prerequisites: EOR E3080. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This is a follow-up to EOR E3600 and will cover advanced topics in optimization, including interior-point optimization, convex optimization, and optimization under uncertainty, with a focus on modeling, formulation, and applications.

EOR E3656y and y Probability for engineers 3 pts.

Prerequisites: ECON UN1011. For undergraduates only. Required for OR:FE concentration. Must be taken during or before third semester. Students who take EOR E3890 may take the third semester due to significant overlap. Recommended for those majoring in IE, OR:EMS, OR:FE, and OR. Must be taken during (or before the fifth semester. Inventory management and probabilistic models are continuous and discrete. Some material is derived from the book models: optimal policies and heuristic solutions. Mathematical requirements: knowledge of basic probability theory and does not assume any prior knowledge of subject. Applications are continuous and discrete in applications, but course itself is theoretical in nature. Basic probability theory definitions and axioms of probability, properties of independence and conditional probability are used.

EOR E3609 Advanced probability and analysis 3 pts.

Prerequisites: EOR E3080. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This is a follow-up to EOR E3600 and will cover advanced topics in probability, including probability, convex optimization, and optimization under uncertainty, with a focus on modeling, formulation, and applications.
Strained nonlinear optimization involving continuous functions. Additionally, fundamental concepts of convexity and duality are discussed, and key duality principle focus on practical optimization methods.


Prerequisites: Linear algebra or instructor's permission. An introductory course in graph theory with an emphasis on applications. Basic definitions, and some fundamental topics in graph theory and its applications. Topics include trees and forests: graph coloring, connectivity, matching, and related graphs.

IEOR E4100 Statistics and simulation 1.5 pts. Lect: 1.5


IEOR E4102 Stochastic models for MSE 3 pts. Lect: 3.


IEOR E4106x and y Stochastic models 3 pts. Lect: 3.

Prerequisites: STAT GU4021 or probability theory or IEOR E4103. The course is offered for IE and OR students. Also required in the Undergraduate Advanced Track. Some of the main stochastic models in engineering applications are: 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 E4106/drom 8010x or Y Supply chain analytics 3 pts. Lect: 2.5

Prerequisite: IEOR E4102 or instructor's permission. MS IEOR students only. Supply chain management, modern design of a supply chain network, inventories, stocks, 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. Notes: replace IEOR 4090 beginning in fall 2018.

IEOR E4111x and y Operations consulting 3 pts. Lect: 3.

Prerequisites: Probability and statistics at the level of IEOR E3608 and E4102, or STAT GU4101, and Deterministic Models at the level of IEOR E3608 or IEOR E4204, or instructor's permission. For MS MSE/MS students only. Aims to help design and implement the management, analytical, and managerial skills needed by 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 students team focuses on identifying, developing, 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 E4112x Probability theory 3 pts. Lect: 3

Prerequisite: Calculus, including multiple integration. Covers the following topics: fundamentals of probability theory and statistical inference used in engineering and applied probabilistic models, random variables, distributions, expectation, law of large numbers, central limit theorem; Statistical independence; Bayes' rule and confidence interval estimation, hypothesis testing, and decision theory. For IEOR graduate students. IEME 4100x or Y Human-centered design & innovation 3 pts. Lect: 3

Prerequisite: IEOR E4150 or instructor's permission. Open to BSE/BS graduate and advanced undergraduate students, Business School, and OR/MSAPP. Students from other schools may apply. Fast-paced introduction to human-centered design. Students learn the vocabulary of design methods, understanding of design process, some design prototypes. Design of simple product, more complex products and services, and design of business.

IEOR E4202x or Y Intellectual property for engineers 3 pts. Lect: 3

Intellectual property (patents, copyrights, trademarks) are increasingly an increasingly important part of any engineering business, as almost any innovation or software or invention, swap, and floors to manage interest rate risk, hedging, and strategies of corporate finance; options using as cheaper options, structured swaps, accounting treatment of derivatives, cash flow hedging, accrual accounting, hedges, hedging of an issuance by using treasury, hedging employee stock options, preferred shares and their use in corporate finance, FRX and FX FYR treatment, commodities hedge, quantitative methods for optimal hedging. Notes: restricted to IEOR MS students.

IEOR E4204x Application of OR & AI techniques in marketing 1.5 pts. Lect: 1.5

Prerequisites: working knowledge of Excel, high level language (such as Python, R, MATLAB, or VBA), and intro in principle of OR: books and online. The course covers mathematical and quantitative methods and data analysis. Topics include clustering methods, conjoint analysis and segmentation, forecasting, census, market share, product life, new product, nearby nearest neighbor, discriminant analysis, decision trees, revenue management, and advertising elasticity, resource allocation and return on ROI, econometric analysis of a network and its formation, and networked markets. Notes: restricted to IEOR MS students only.

IEOR E4205x Corporate finance, accounting, & investment banking 3 pts. Lect: 3

Prerequisite: Covers primary financial theories and alternative theories underlying Corporate Finance, such as CAPM, BlackScholes, risk parity, Markowitz, Value at Risk, Smart Beta, etc. Interpret financial statement analysis, investment decision analysis, risk, cost of capital, valuation, taxation, dividend policy, bankruptcy, and return on investment (ROI), economic behavior and return of capital. A mathematically rigorous study of financial theory, mechanism design, optimal allocation, auction, and decision theory in applied settings. No previous knowledge of game theory is required.

IEOR E4206x Quantitative corporate finance 3 pts. Lect: 3

Prerequisite: Probability theory and linear programming. Required for students in the Undergraduate Advanced Track. Required for students to understand 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 y Simulation 4 pts. Lect: 3

Prerequisites: IEOR E3608 and E4307 or STAT GU4307. Computer Simulation. Concepts: IEOR E3010 or IEOR E4107. Required for all undergraduate students majoring in IE, OR/MS, or ORIE, and also required for M.SQR. Generation of random numbers from various distributions, variance reduction techniques, simulation output analysis. Required for students in IE. Sensory and cognitive (brain) processing and motivation.

IEOR E4408x Game theory models of operations 3 pts. Lect: 3

Prerequisites: IEOR E4402 or (EI4304) and (EI4106), familiarity with optimization and partial differential equations, and computer programming; or instructor’s permission. Required for undergraduate students majoring in OR and IE. Job shop scheduling for parallel machines, machine in series; assembly job shops. Algorithms, complexity, and worst case analysis. Effects of randomness: machine breakdown, random processing time. Term project.

IEOR E4407x Game theoretic models of operations 3 pts. Lect: 3

Prerequisites: IEOR E4404 or (EI4304) and (EI4106), familiarity with optimization and partial differential equations, and computer programming; or instructor’s permission. Required for undergraduate students majoring in OR and IE. Job shop scheduling for parallel machines, machine in series; assembly job shops. Algorithms, complexity, and worst case analysis. Effects of randomness: machine breakdown, random processing time. Term project.

IEOR E4408x Resource allocation models: algorithms, and applications 3 pts. Lect: 3

Prerequisite: IEOR 4310, 4311, 4313. Not offered in 2020-2021.

IEOR E4408x Game theory models of operations 3 pts. Lect: 3

Prerequisites: IEOR E4404 or E4304, basic knowledge of network and integer programming. Overview of one of several allocation models. Single resource allocation with concave return; equitable resource allocation; logisographic minimax/mimimax optimization; equilibrium models for network resource allocation; equitable allocation in multicommodity flow problems. Note: restricted to IEOR MS students only.

IEOR E4412x Quality control and management of processes 3 pts. Lect: 3

Prerequisites: IEOR E3658 and building knowledge of statistics required for undergraduate students majoring in IE. Statistical methods for quality control and reliability. Introduction to experimental design and reliability engineering and the relationships between quality and productivity. Note: restricted to manufacturing and service organizations in product and process design, production, and delivery of products and services.

IEOR E4413x Transportation and logistics 3 pts. Lect: 3

Prerequisites: IEOR E3608 or E4404 or instructor’s permission. Required for undergraduate students majoring in IE, OR/MS, or ORIE, and also required for M.SQR. Generation of random numbers from various distributions, variance reduction techniques, simulation output analysis. Required for students in IE. Sensory and cognitive (brain) processing and motivation.
IEOR 4526x Systems engineering and tools 3 pts. Lect: 3. Prerequisites: IEOR E422x or E420x. B.S. in engineering or applied sciences; probability and statistics, optimization, linear algebra, and basic economics. Applications of tools and methods in various settings. Encompasses modern system complex development environments, including aerospace and control systems, distributed systems, and modern software-intensive systems.

IEOR 4524x and y Data analytics 3 pts. Lect: 3. Corequisites: IEOR 4522 or 4501. Students only: priority to MSBA students. Survey data tools available in Python for getting, cleaning, and examining data. Obtain data from Nieuw (crowd-sourcing, cleaning, and examine data analysis, machine learning, and data visualization packages [Pandas, R, 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 allow students to gather, store, and analyze a data set of their choosing.

IEOR 4524x Analytics in practice 3 pts. Lect: 3. Prerequisites: IEOR E4322 or 4001 and IEOR E4523. MSBA students only. Groups of students work on real-world projects in analytics, focusing on three aspects of client-facing client analytical techniques (STAT, OR, machine learning); and delivering results in a client-friendly format. Each project group has access to a data pool of 26 different data sets, and has been structured so that it can be conducted in one semester with numerous on-site clients; students should pick projects for the purpose.

IEOR 4549x Financial engineering and management 3 pts. Lect: 3. Prerequisites: IEOR E420x or E4206 or IEOR E4320, 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 4530x Applied systems engineering 3 pts. Lect: 3. Prerequisites: IEOR E4206 or IEOR E4204, IEOR E4523x and y. Data analytics, Data science, and modern software-intensive systems. Focus on system services viewed as stochastic networks, exploiting the theoretical framework of queueing theory. Includes multidisciplinary perspectives involving Statistics, Psychophysics, and Marketing, and incorporates new data tools from banks, hospitals, and call centers to demonstrate the use of decision support tools. Analytical models, flow of network service. Little's law, measuring in terms of traffic load and computerized systems, functioning in feedback stability of service systems, operational quality of service, economical measures, and soft-core service networks, skill-based routing.

IEOR 4540x Pricing models for financial engineering 3 pts. Lect: 3. Prerequisites: IEOR E4700x and y. Introduction to investment and financial engineering simulation software and exposure to register for this course for credit.

IEOR 4570x Monte Carlo simulation 3 pts. Lect: 3. Prerequisites: IEOR E4701. This 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. Markov chains and applications to queuing theory. Inventory models, branching processes.

IEOR 4576x Foundations of financial engineering 3 pts. Lect: 3. Prerequisites: IEOR E4701, E4702, and IE4701. Student must register in Program in Financial Engineering student, offered during the summer session. Discrete-time models of equity, bond, and foreign-exchange horizons, and pricing of fixed-income derivatives.

IEOR 4670 Financial engineering: Derivatives and asset pricing
3 pts. Lect. 3

IEOR 4706 Fixed income and term structure modeling
3 pts. Lect. 3
Prerequisites: Probability and IEOR 4670. Corequisites: IEOR 4706, 4707. This graduate course is only for M.S. Program in Financial Engineering students. Analysis of yield curves, term structure, and term structure modeling. Advanced topics in fixed income markets and fixed income securities. Description and applications of various interest rate models. Discussion of the practical implementation of these models.

IEOR 4714x Global capital markets 3 pts. Lect. 3
Prerequisites: Refer to course syllabus. An introduction to global capital markets and investments providing an overview of financial markets and tools for asset valuation. Topics covered include the nature of fixed-income securities (topics on the markets, interest rate swaps futures, etc.), discussions on topics in credit, foreign exchange, derivatives and futures, trading markups—plain vanilla and hedge funds, etc.

IEOR 4712x Behavioral finance 1.5–3 pts. Lect. 1.5–3
Prerequisites: IEOR 4704. Behavioral finance is the application of behavioral psychology to finance and economics. Focuses on the portfolio aspect of behavioral finance and briefly touches on other aspects. Considers applied research on how the theory of portfolio choice, behavioral portfolio choice features human being's psychological biases. It builds on the ideas of modern finance and extends them to the behavioral finance area. The three special problems: market efficiency, investor behavior, and asset pricing. 

IEOR 4741x Investment management and portfolio optimization 3 pts. Lect. 3
Prerequisites: IEOR 4700, 4720, or 4734. This course is offered concurrently with FINC 4741. This course is only for M.S. Program in Financial Engineering students. Introduction to investment management and portfolio optimization. Focuses on the development of quantitative models for asset allocation, risk management, and asset valuation. Special topics in portfolio management, including the capital asset pricing model, mean-variance analysis, and the Markowitz model. The course is designed for students interested in careers in investment banking, asset management, and other areas related to financial services.

IEOR 4744x Risk Management 3 pts. Lect. 3
Prerequisites: IEOR 4700. Corequisite: IEOR 4707. This course is only for M.S. Program in Financial Engineering students. Risk management is the systematic approach to identifying, assessing, and managing the risks associated with a financial asset or project. The course covers the role of risk management in the financial services industry, including the concepts of risk management, risk measurement, and risk mitigation. The course also covers the implementation of risk management strategies, including the use of financial instruments such as insurance, hedging, and derivative securities.

IEOR 4745x Applied financial risk management 1.5 pts. Lect. 1.5
Prerequisites: IEOR 4700. Corequisites: IEOR 4706, 4707. This course is only for M.S. Program in Financial Engineering students. Provides a practical introduction to financial risk management, including the implementation of risk management strategies in various financial markets. The course covers the use of quantitative models for risk management, including the Capital Asset Pricing Model (CAPM), the Black-Scholes model, and other models for pricing financial derivatives. The course also covers the use of financial instruments such as options, futures, and swaps for risk management.

IEOR 4748x Computational methods in finance 3 pts. Lect. 3
Prerequisites: IEOR 4701 and E4707. This course is only for M.S. Program in Financial Engineering students. Provides an introduction to computational methods for solving financial problems, including numerical methods for solving partial differential equations. The course covers techniques such as finite difference methods, Monte Carlo simulation methods, and calibration techniques. The course also covers the use of software tools for implementing computational methods.

IEOR 4754x Financial modeling and market making in foreign exchange 1.5 pts. Lect. 1.5
Prerequisites: IEOR 4700, 4707. Corequisite: IEOR 4744. This course is only for M.S. Program in Financial Engineering students. Provides an introduction to financial modeling and market making in foreign exchange, including the use of financial instruments such as forwards, options, and swaps for hedging and speculation. The course also covers the use of software tools for implementing financial models in foreign exchange markets.

IEOR 4798x Financial Engineering 3 pts. Lect. 3
Prerequisites: IEOR 4700, 4706, 4707, and 4714. Corequisite: IEOR 4744. This course is only for M.S. Program in Financial Engineering students. Provides an introduction to financial engineering, including the use of financial instruments such as options, forwards, and futures for hedging and speculation. The course also covers the use of software tools for implementing financial models in foreign exchange markets.

IEOR 4998x Master’s project or research 1–3 pts. Members of the faculty. 

IEOR 4998b Managing technological innovation 3 pts. Lect. 3
Prerequisites: Refer to course syllabus. Focus on the management and consequences of technology innovation. Examines the relationship between technology and the creation of wealth and the management challenges of pursuing strategic innovation.

IEOR 5405s, x and y Fieldwork 1–3 pts. (up to 2 semesters only)
Prerequisites: Obtained internship and approval from the faculty. Open only to master's students who need relevant work experience as part of their program of study. Final reports required. May not be taken for past credit or audit.
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.

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MATERIALS SCIENCE AND ENGINEERING

Marcelo Aron Pinczuk
Professor of Materials Science

Ismail C. Noyan
Professor of Materials Science

Yuan Yang
Associate Professor of Materials Science

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 ultrapapid solidification of thin films; radiation 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 ultrastiff 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 Characterization. Facilities and research opportunities also exist within the interdepartmental 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, mechanical 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; electronic nanostructures for information storage and novel computer 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 this 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 indicated in the list given below, which offers significant flexibility in allowing students to tailor their degree program to their interests.

### a. At 3000-level or higher in the Materials Science program of the Department of Applied Physics and Applied Mathematics, except those MSAE courses that are required.

### b. At 3000-level or higher in the Materials Science program of the Department of Applied Physics and Applied Mathematics.

### c. At 3000-level or higher in courses in Applied Physics or Applied Mathematics.

### d. At 3000-level or higher courses in the 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.

### e. Courses in the Department of Chemistry listed in the Focus Areas below.

- **FOCUS AREAS**: Students may choose from any one of these areas if they so choose. They are not required to do so.

**NANOMATERIALS**

**APPM E3400y**: Intro to quantum mechanics

**CHEM GU4048y**: Inorganic chemistry

**CHEM GU4089y**: Nanotechnology

**ENGR E4301x**: Physics of matter in microelectromechanical systems

**ENME E4115y**: Physical chemistry of solids

**MATERIALS FOR GREEN ENERGY**

**CHEE E4505x**: Industrial and environmental electrophotography

**CHEM GU4710x**: Inorganic chemistry

**EAPP E4130x**: Physics of solar energy

**EASE E4190x**: Prototypes systems engineering and sustainability

**EASA E4505x**: Alternative energy resources

**MATERIALS FOR 21ST CENTURY INFRASTRUCTURE AND MANUFACTURING**

**GEE E3250x**: Environmental control and pollution reduction systems

**GEE E3250x**: Environmental development communities

**MATERIALS FOR HEALTH AND BIOTECHNOLOGY**

**CHEM UN3240x** and **CHEM UN3241y**: Organic chemistry

**APPH E3600x**: Physics of the human body

**CHEM GU4188x**: Materials chemistry

**BMEN E4101h**: Thermodynamics of biological systems

**BMEN E4301x**: Structure, mechanics, and adaptation of bone

**BMEN E4101x**: Solid biomaterials

**CHEE E4505x**: Industrial and environmental electrophotography

**CHEM GU4710x**: Inorganic chemistry

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**BMEN E4101x**: Solid biomaterials
Students transferring from another SEAS department into the Materials Science program in the junior year must complete the 27-point requirement; see page 9 or Combined Plan 3/2 transfer students must complete 24 units of technical electives.

NONTECHNICAL ELECTIVES

- Students must complete 27 units of Technical Electives.

- Students must complete the 27-point requirement.1

- Motivated 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.

MATERIALS SCIENCE PROGRAM: THIRD AND FOURTH YEARS

SEMMESTER V SEMESTER VI SEMESTER VII SEMESTER VIII

REQUIRED COURSES

- MSAE E3012 (3) Laboratory in materials science, I
- MSAE E3013 (3) Laboratory in materials science, II
- MSAE E4100 (3) Materials thermodynamics and phase diagrams
- MSAE E4102 (3) Synthesis and processing of materials
- MSAE E3156 (2) Design project
- MSAE E4002 (3) Theory of crystalline materials
- MSAE E4006 (3) Electronic and magnetic properties of solids
- MSAE E3157 (2) Design project
- MSAE E4002 (3) Kinetics of transformations in materials
- MSAE E4215 (5) Mechanical behavior of materials

- Materials science laboratory I
- Materials science laboratory II
- Materials science, I
- Materials science, II
- Materials thermodynamics and phase diagrams
- Synthesis and processing of materials

NONTECHNICAL ELECTIVES

- Students must complete 27 units of Technical Electives.

- Students must complete the 27-point requirement.2

1 Motivated 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.

2 See page 9 or our columbia.edu for details (administered by the adems dean).

MATERIALS SCIENCE PROGRAM: THIRD AND FOURTH YEARS (TRANSFER STUDENTS)

SEMMESTER V SEMESTER VI SEMESTER VII SEMESTER VIII

REQUIRED COURSES

- MSAE E3010 (3) Foundations of materials science and engineering
- MSAE E3012 (3) Laboratory in materials science, I
- MSAE E3013 (3) Laboratory in materials science, II
- MSAE E3156 (2) Design project
- MSAE E4100 (3) Materials thermodynamics and phase diagrams
- MSAE E4102 (3) Synthesis and processing of materials
- MSAE E3157 (2) Design project
- MSAE E4002 (3) Kinetics of transformations in materials
- MSAE E4215 (5) Mechanical behavior of materials

NONTECHNICAL ELECTIVES

- Students must complete 27 or 24 units of Technical Electives.1

- Students must complete the 27-point requirement.2

1 Students 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.

2 Students transferring from another SEAS department into the Materials Science program in the junior year must complete the 27-point requirement; see page 9 or columbia.edu for details (administered by the adems dean). Combined Plan 3/2 transfer students do not need non-technological electives; see page 14 or columbia.edu.

27 points: MSAE E4100: Materials science laboratory; MSAE E4200: Electronic and magnetic properties of solids; MSAE E4215: Mechanical behavior of structural materials

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, E3156, E3157, E4000, E4002, E4200, E4201, E4202, E4203, E4204, and E4205.

Combined Plan 3-2/Transfer Students

27 points: MSAE E4100: Materials science laboratory; MSAE E4200: Electronic and magnetic properties of solids; MSAE E4215: Mechanical behavior of structural materials

Graduate Programs in Materials Science and Engineering

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Ph.D. students must complete strongly encouraged to complete ENGI E6001–E6004 and should consult their program for 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 are required at a minimum. 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.

The following six courses (18 points) are required for the degree. Students must take a minimum of two of the six required courses, one of which must be MSAE E4100 Crystallography, in their first semester. 18 points:

MSAE E4150: Crystallography
- MSAE E4200: Theory of crystalline materials: phonons
- MSAE E4201: Materials thermodynamics and phase diagrams
- MSAE E4202: Kinetics of transformations in materials
- MSAE E4204: Electronic and magnetic properties of solids
- MSAE E4215: Mechanical behavior of structural materials

If a candidate has already taken one or more of these courses at Columbia University, substitutions from the Electives list must be approved by their faculty adviser and approval of the program committee. The remaining 12 points will be chosen from elective courses.

Electives:

- MSAE E4900: Nanotechnology
- MSAE E4910: Statistical analysis of materials
- MSAE E4915: Synthetic and processing of materials
- MSAE E4915: Ceramic nanomaterials
- MSAE E4932: Fundamentals of polymers and ceramics
- MSAE E4932: Theory of crystalline materials: electrons
- MSAE E4940: Ceramics and composites
- MSAE E4960: Electrochemical materials and devices: from structure to performance
- MSAE E4970: Materials science laboratory
- MSAE E4990: Special topics in materials science and engineering

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Ph.D. students must complete strongly encouraged to complete ENGI E6001–E6004 and should consult their program for PDL requirements.

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M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. Ph.D. students must complete strongly encouraged to complete ENGI E6001–E6004 and should consult their program for PDL requirements.
who wish to do advanced work beyond the level of the M.S. degree but who do not desire to emphasize research.

Admission to the graduate program involves the undergraduate engineering degree, mini-

mum 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 taken to count toward the degree.

Coursework includes five core required courses and five elective courses from a pre-approved list of choices.

1. **EAE34011 Industrial ecology of earth**
2. **EAE4109 Geophysical information systems**
3. **EAE4116 Solid and hazardous waste materials**
4. **EAE4190 Applied transport/chemical rate phenomena**
5. **EAE4125-6 Methods and applications of analytical decision making in mineral industries**

Effective courses must be taken at the senior or higher level from within the Earth and Environmental Engineering Department, the Chemical Engineering Department, the Materials Science Department, or others as approved by the advisor. These include but are not limited to:

- EAE34110, CHEE 4292, ECE 4202, EAE4205, EAE4257, EAE4260. Although not required, interested students may choose to complete up to six credits in MSAE E5259-6.

**Doctoral Program**

At the end of the first year of graduate study in the doctoral program, candidates are required to take a comprehensive examination, which is designed to test the ability of the candidate to apply coursework in problem solving and research. Students must pass the standard first-year graduate level. There are two four-hour examinations over a two-day period. All 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 advisor 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 from outside the doctoral program. Requirements for the Eng.

- ECE 4202 (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 the bulletin.

**Areas of Research**

Materials science and engineering is concerned with the synthesis, processing, structure, and properties of metals, ceramics, and other materials, with emphasis on understanding and exploiting relationships among structure, properties, and applications. First-year graduate courses provide a common base of knowledge and technical skills for more advanced coursework and for research. In addition, 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-state materials, with special emphasis on electrical, magnetic, optical, and thermal properties. The science of solids is concerned with understanding the electronic and atomic structure through experimental and theoretical study of materials. It is important in a number of practical applications.

The doctoral student must meet the following minimum requirements for the Ph.D. degree, subject to the recommendation of the student and a professor in the department. The student must pass the written examination covering the subjects in the first year of the course, and the oral examination in the spring semester of the second year.

- **Introduction to quantum mechanics:** atoms, electrons shells, bonding, introduction to group theory: crystal structures, symmetry, crystallography, introduction to materials: metals, ceramics, polymers, liquid crystals, amorphous materials.
- **Modern optical theory:** lasers, light scattering in low-dimensional systems, and biological materials.
- **Solid state physics:** electronic structure, band theory, solid state properties of metals and semiconductors, band theory of solids.
- **Semiconductor devices:** principles of device microfabrication, principles of semiconductor materials, and modern device fabrication techniques.
- **Electrical, thermal, and magnetic properties of semiconductors:** electrical and magnetic properties of semiconductors, magnetic properties of solids, magnetic properties of materials, magnetic properties of materials, and ferroics.
- **Statistical mechanics:** statistical thermodynamics, statistical mechanics, and phase transitions.
- **Atomic structure of solids:** crystallography, crystal chemistry, and crystallography of materials.
- **Solid state and engineering:** solid state science and engineering.

The following are regarded as core courses of the doctoral program:

- **APPH E4111:** Optical physics of materials
- **APPH E4112:** Laser physics
- **APPH E4113:** Modern optics
- **CHEM 4220:** Statistical thermodynamics
- **CHAP E4210:** Statistical mechanics

**ELEN E4044:** Principles of device fabrication

**ELEN E4050:** Cryogenics

**ELEN E6040:** Classical electromagnetic theory

**PHYS GR6002:** Electromagnetic theory

**MSAE E4025:** Electrostatics and magnetic properties of solids

**PHYS GR6018:** Physics of the solid state

**PHYS GR6028:** Quantum mechanics

**COURSES IN MATERIALS SCIENCE AND ENGINEERING**

For related courses, see also Applied Mathematics and Engineering, Electrical Engineering, and Mechanical Engineering.

**MSAE E3201x Foundations of materials science**

3 pts. Lect: 3. Professor Bliokh.

**PHYS E4101:** The science of solids: an introduction to modern technology that no single department can provide. It encompasses the study of the full range of properties of solid-state materials, with special emphasis on electrical, magnetic, optical, and thermal properties. The science of solids is concerned with understanding the electronic and atomic structure through experimental and theoretical study of materials. It is important in a number of practical applications.

The doctoral student must meet the following minimum requirements for the Ph.D. degree, subject to the recommendation of the student and a professor in the department. The student must pass the written examination covering the subjects in the first year of the course, and the oral examination in the spring semester of the second year.
directional reading, and regular conferences with the professor in charge. E1357: Completion of the dissertation, oral defenses, and final conferences, written in a calm report and an oral presentation to the department.

**MSE A100x and y Undergraduate research in materials science**

3–4 pts. Members of the faculty. Prerequisites: MSE A101x or institution’s permission. The science and engineering of creating materials, functional structures and devices using advanced nanomaterials. Prerequisites: CHEM UN1403, PHYS UN1403, or the equivalent with permission of the instructor. The science and engineering of creating materials, functional structures and devices using advanced nanomaterials. Prerequisites: CHEM UN1403, PHYS UN1403, or the equivalent with permission of the instructor.

**MSE A140x Nanotechnology**

3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: MSE A101x or institution’s permission. The science and engineering of creating materials, functional structures and devices using advanced nanomaterials. Prerequisites: CHEM UN1403, PHYS UN1403, or the equivalent with permission of the instructor.

**MSE A140Y Nanotechnology**

3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: APHY E130x and MSE A1010 or the equivalent with permission of the instructor. The science and engineering of creating materials, functional structures and devices using advanced nanomaterials. Prerequisites: CHEM UN1403, PHYS UN1403, or the equivalent with permission of the instructor.

**MSE A152x Synthesis and processing of materials**

3 pts. Lect. 3. Professor Im. Preferable prerequisite: CHEM UN1404 or equivalent undergraduate undergraduate nanomaterials. Ceramics, nanomaterials and nanoscience: synthesis, characterization, size-definition properties, and applications; surface energy, surface tension and surface stress; effect of ligands, surfactants, and adsorbed species in colloidal systems; solution and precipitation of colloidal systems; surface charge; stabilization and homogeneity nucleation for monodispersity.

**MSE A142y Fundamentals of polymers and ceramics**

3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: MSE A101x or institution’s permission. The science and engineering of creating materials, functional structures and devices using advanced nanomaterials. Prerequisites: CHEM UN1403, PHYS UN1403, or the equivalent with permission of the instructor.

**MSE A1200 Theory of crystallographic materials**

3 pts. Lect. 3. Professor Marianetti. Prerequisites: MSE A142x or institution’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, free and self-consistent function, density functional transport, magneto, optical properties, topological insulators, spin–orbit coupling, and superconductivity. Both minimal and maximal model Hamiltonians in addition to accurate Hamiltonians for real materials.

**MSE A160x Electronic and magnetic properties of solids**

3 pts. Lect. 3. Professor Baley. Prerequisites: PHYS UN1401 or equivalent. A course on the survey of electronic and magnetic properties of materials, oriented toward materials for solar cells and their magnetic properties, ferromagnets, and magnets. Conductivity and superconductivity. Electronic band theory of solids: classification of metals, insulators, and semiconductors. Materials in device, example: magnetic recording, spintronics, polarized light, capacitive transport, integrated circuits, and magnetic storage. Additional experiments at discretion of instructor.

**MSE A145y Mechanical behavior of structural materials**


**MSE A142y Kinetics of transformation in materials**

3 pts. Lect. 3. Professor Im. Prequisites: MSE A142x or institution’s permission. Review of thermodynamics, irreversible thermodynamics, diffusion in crystals and their evolution, defects, chemical, transport, and electrical properties of ceramic materials. Following this, we will examine application of tensorial and boundary values, specifically, ceramic thick and thin films material in the areas of sensors and energy conversion/ storage, electronic, optical and magnetic devices. The course work level assumes that the student has already taken basic courses in the thermodynamics of materials, diffusion in materials, and crystal structures of materials.

**MSE A141x Thin films and layers**

3 pts. Lect. 3. Professor Wenzelworth. Prerequisites: CHEM UN1403 or equivalent. Basics of density functional theory (DFT) and its application to complex materials. Computation of electronic and mechanical properties of materials. Group theory, numerical methods, basis sets, computing, visualization, and electronic and defect DFT codes. Problem sets and a small project.

**MSE A160y Magnetism and magnetic materials**


**MSE A160y Transmission electron microscopy**

3 pts. Lect. 3. Not offered in 2020–2021. Prerequisites: permission of the instructor. Theory and practice of transmission electron microscopy (TEM): principles of electron scattering, diffraction, and microscopy, analysis of planar defects, and determination of local chemistry. Introduction to sample preparation; laboratory and in-class remote access demonstrations. Review of TEM and lab microscopy. The use of computer 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).

**MSE A162y Energy and particle beam processing of materials**


**MSE A162y Kinetics of phase transformations**


**MSE A162y Thin films and layers**

3 pts. Lect. 3. Professor Chart. Prerequisites: Vacuum basics, deposition method, nucleation and growth, epilayer, critical thickness, defects properties, effect of deposition procedure, and mechanical properties, adhesion, interconnects, and electromigration.

**MSE A627x and y–S627 Materials science reports**

3 pts. Members of the faculty. Prerequisites: Written permission from instructor and approval from the Department of Materials Science and Engineering. Formal written reports and conferences with the appropriate member of the faculty and the course instructor. May be repeated for credit. Selected topics in materials science. Topics and instructors change from year to year. For doctoral degree in materials science and metallurgical engineering.

**MSE A499x and y–S499 Research topics in materials science and metallurgical engineering**

1–3 pts. Members of the faculty. Prerequisites: Qualifying examination for doctorate. Required of doctoral candidates.

**MSE A501x and y–S501 Doctoral research**

1–3 pts. Members of the faculty. Prerequisites: Qualifying examination for doctoral degree

**MSE A162y and y–S162 Doctoral research**

1–3 pts. Members of the faculty. Prerequisites: Qualifying examination for doctoral degree

**MSE A690x and y–S690 Doctoral instruction**

1–3 pts. Members of the faculty. Prerequisites: For the Eng.Sc. degree must register for 12 points of doctoral instruction each term, and 15 points of doctoral instruction may not be used to satisfy the minimum residence requirement for the degree

**MSE A695y–S695 Dissertation**

2 pts. Members of the faculty. A candidate for the doctorate in materials science and engineering is required to register for this course every term after the coursework has been completed and until the dissertation has been accepted.
Mechanical engineering is a diverse subject that covers a wide breadth from the need to design and manufacture everything from small individual parts (e.g., microscale sensors, inkjet printer nozzles) to large systems (e.g., spacecraft and aircraft). This breadth of mechanical engineering 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 and ability to withstand the forces and the thermal environment that a product, its parts, or its subsystems will encounter; design them to meet several sometimes conflicting requirements. The mechanical engineering discipline allows students to select courses to meet their design goals, the ability to design exciting objects that allows them to design an exciting product or system, the analytical tools to achieve their design goals, the ability to determine the best way to manufacture a product, its parts, or its subsystems will encounter; design them to meet several sometimes conflicting constraints, and the teamwork needed to develop the design, market, and produce a system. These skills also prove to be valuable in other endeavors and can help in one’s career; design, consulting, management, banking, finance, and so on.

For example, students 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.
Biomechanics and Mechanics of Materials. Some of the current research in biomechanics is concerned with the application of continuum electromechanics to problems of mechanical behavior of soft biological tissues, contact mechanics, lubrication of diarthrodial joints, and cartilage tissue engineering (Agrawal).

For those interested in applied engineering and the application of basic science to practical problems, our research efforts center on mechatronics, which is a fusion of mechanical engineering, control systems for airplanes (from the car chassis to its every mechanical engineers play a central role in the broadest and most diverse part of the discipline, design, and manufacture of systems for efficient use of variable renewable energy. The development of measurement, monitoring, and control systems using IoT devices for use in microturbines and optimization of microturbines 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 control automation in manufacturing and logistics, assistive and rehabilitation robotics in healthcare, space robotics, and mobile manipulation in unstructured environments. (Ciccarone) 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-evolving, satellite precision pointing, particle accelerators, etc. Time optimal control of robots is being studied for increased productivity of assembly lines through dynamic motion planning. Research is also being conducted on improved system identification, 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 robots and training algorithms for functional rehabilitation of neuromotor impaired adults and children. The research also aims to design intelligent machines using computational algorithms for planning, and optimization.

Robotics 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 control automation in manufacturing and logistics, assistive and rehabilitation robotics in healthcare, space robotics, and mobile manipulation in unstructured environments. (Ciccarone) 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-evolving, satellite precision pointing, particle accelerators, etc. Time optimal control of robots is being studied for increased productivity of assembly lines through dynamic motion planning. Research is also being conducted on improved system identification, 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 neuromotor impaired adults and children. The research also aims to design intelligent machines using computational algorithms for planning, and optimization.

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transport across interfaces separated by a nanoscale gap. The scaling behavior of nanoscale devices and circuits is crucial for understanding the role of mechanical properties of nanomaterials in the performance of nanoscale electronic behavior that governs molecular reactivity to the large-scale...
The department maintains a modern equipment in these research facilities. The students laboratories within the research section capabilities please visit the various research laboratories in the department, located within individual or group software. The research facilities are stations with state-of-the-art design and development, and other creative efforts in science, technology, and innovation. 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.

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**Mechanical Engineering Program: First and Second Years**

**Standard Track**

<table>
<thead>
<tr>
<th>SEMESTER I</th>
<th>SEMESTER II</th>
<th>SEMESTER III</th>
<th>SEMESTER IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH UN1101 (3)</td>
<td>MATH UN1102 (3)</td>
<td>APMA E2000 (4) and ORCA E2500 (8)*</td>
<td>APMA E2101 (3)* or Linear Algebra (3)* and ODE (3)*</td>
</tr>
<tr>
<td>UN1401 (3)</td>
<td>UN1402 (3)</td>
<td>UN1403 (3)*</td>
<td>UN1402 (3)</td>
</tr>
<tr>
<td>UN1601 (3.5)</td>
<td>UN1602 (3.5)</td>
<td>UN1603 (3.5)*</td>
<td>UN1602 (3.5)</td>
</tr>
<tr>
<td>PHYSICS (three tracks, choose one)</td>
<td>CHEMISTRY (one semester lecture (3-4) or UN1403 or UN1404 or UN2045 or UN1604)</td>
<td>Lab UN1500 (3)*</td>
<td></td>
</tr>
</tbody>
</table>

**University Writing**

CC1010 (3) or other semester

**Required NonTechnical Courses**

| HUMA CC1001, or COCI CC101, or Global Core (3-4) | HUMA CC1002, or COCI CC1002, or Global Core (3-4) | EDON UN1100 (4) and UN1155 recitation (0) |

**Technical Electives**

| MEEC E3008 (3) | MEEC E3009 (3) | MEEC E3010 (3) |

**Electives 1**

3. Students must complete a minimum of 128 points to graduate.

6. Students must complete 15–16 credits.

**Total Estimated Points**

15–16

16.5–17.5

16

15

1. Strongly recommended to be taken in Semesters III or IV.

2. 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, BIOC, ORTH, APMA, or EEEB. One technical elective (3000-level or higher) may be substituted for this purpose.

3. Linear algebra may be fulfilled by either APMA E3101 or MATH UN1005.

4. Ordinary differential equations may be fulfilled by either MATH UN1200 or MATH UN1202.

5. May substitute EEB UN1201, BIOC UN3003, or higher.

6. May substitute Physics Lab UN1443 (3) or UN3081 (3).

7. Offered in spring semester.

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).

**MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS**

**Standard Track**

<table>
<thead>
<tr>
<th>SEMESTER V</th>
<th>SEMESTER VI</th>
<th>SEMESTER VII</th>
<th>SEMESTER VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEEC E3018 (3)</td>
<td>MEEC E3028 (5)</td>
<td>MEEC E3400 (3) or MEEC E3405 (3)</td>
<td>MEEC E3405 (3)</td>
</tr>
<tr>
<td>MEEC E3100 (3)</td>
<td>MEEC E3106 (3)</td>
<td>MEEC E3410 (3)</td>
<td>MEEC E3410 (3)</td>
</tr>
<tr>
<td>MEEC E3301 (3)</td>
<td>Fluids I</td>
<td>MEEC E3411 (3)</td>
<td>MEEC E3415 (3)</td>
</tr>
<tr>
<td>MEEC E3408 (3)</td>
<td>Thermodynamics</td>
<td>Heat transfer</td>
<td>Machine design: concept</td>
</tr>
<tr>
<td>ENME E3113 (3)</td>
<td>Mechanics of solids</td>
<td>MEEC E3410 (3)</td>
<td>MEEC E3415 (3)</td>
</tr>
</tbody>
</table>

**Required Courses**

| MEEC E1005 (1) Intro to machining (if other semester) |

**Technical Electives**

6 points

**Electives 2**

3. Students must complete the 27-point requirement.

4. Students must complete a minimum of 128 points to graduate.

5. 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, BIOC, ORTH, APMA, or EEEB. One technical elective (3000-level or higher) may be substituted for this purpose.


7. See page 2 for requirements for Combined Plan students.

8. Students must complete a minimum of 128 points to graduate.

9. Students must complete a minimum of 128 points to graduate.

10. Students must complete 15–16 credits.

**Total Estimated Points**

15–16

16.5–17.5

16

15

1. Strongly recommended to be taken in Semesters III or IV.

2. Linear algebra may be fulfilled by either APMA E3101 or MATH UN1005.

3. Additional differential equations may be fulfilled by either MATH UN1200 or MATH UN1202.

4. May substitute EEB UN1201, BIOC UN3003, or higher.

5. May substitute Physics Lab UN1443 (3) or UN3081 (3).

6. Offered in spring semester.

7. Choose one.

8. Choose one.

9. Choose one.

10. Choose one.

11. Choose one.

12. Choose one.

13. Choose one.

14. Choose one.

15. Choose one.

16. Choose one.

17. Choose one.
MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
EARLY DECISION TRACK

<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 CIRCA E2500 (2) or APMA E2101 (3) or Linear Algebra (3) or ODE (3)</td>
</tr>
<tr>
<td><strong>PHYSICS</strong></td>
<td>UN101 (3)</td>
<td>UN1051 (3.5)</td>
<td>UN1403 (3) or UN2601 (3.5)</td>
</tr>
<tr>
<td><strong>CHEMISTRY</strong></td>
<td>one semester lecture (3–4)</td>
<td>UN1403 or UN1404 or UN2045 or UN1654</td>
<td>Lab UN1500 (3)</td>
</tr>
<tr>
<td><strong>UNIVERSITY WRITING</strong></td>
<td>CC1010 (3)</td>
<td>either semester</td>
<td></td>
</tr>
<tr>
<td><strong>REQUIRED COURSES</strong></td>
<td>ENME E1105 (4) Mechanics</td>
<td>ENME E1113 (3) Mechanics of solids</td>
<td>ELEN E1107 (3.5) Intro. to elec. eng.</td>
</tr>
<tr>
<td><strong>REQUIRED TECHNICAL COURSES</strong></td>
<td>Computer language: COMS W1004 or COMS W1005 (3) or ENGI E1006 (3) in semester I and III</td>
<td></td>
<td>MECE E3408 (3) Graphics and design</td>
</tr>
<tr>
<td><strong>TOTAL ESTIMATED POINTS</strong></td>
<td>6 points</td>
<td>6 points</td>
<td>4 points</td>
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</tbody>
</table>

**MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS
EARLY DECISION TRACK**

<table>
<thead>
<tr>
<th>SEMESTER V</th>
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<th>SEMESTER VII</th>
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<tr>
<td><strong>REQUIRED COURSES</strong></td>
<td>MECE E3018 (3)</td>
<td>Lab I</td>
<td>MECE E3018 (3)</td>
</tr>
<tr>
<td><strong>MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS</strong></td>
<td>MECE E3000 (3) Design and vibrations</td>
<td>MECE E3311 (3) Heat transfer</td>
<td>MECE E3400 (3) Machine design</td>
</tr>
<tr>
<td><strong>MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS</strong></td>
<td>MECE E3301 (3) Thermodynamics</td>
<td>MECE E3310 (3) Materials and processes in manufacturing</td>
<td>MECE E3420 (3) Engineering design: concept</td>
</tr>
<tr>
<td></td>
<td>MECE E3028 (3)</td>
<td></td>
<td>MECE E3601 (3) Classical control systems</td>
</tr>
<tr>
<td></td>
<td>MECE E3302 (3)</td>
<td></td>
<td>MECE E3430 (3) Engineering design: creation</td>
</tr>
<tr>
<td><strong>MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS</strong></td>
<td>MECE E3306 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS</strong></td>
<td>MECE E1008 (1) Intro to machining (either semester)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>REQUIRED NONTECHNICAL COURSES</strong></td>
<td>HUMA UN1121 or UN1123 (3)</td>
<td>ECON UN1105 (4) and UN1155 recitation (5)</td>
<td></td>
</tr>
<tr>
<td><strong>TECHNICAL ELECTIVES</strong></td>
<td>6 points</td>
<td>6 points</td>
<td></td>
</tr>
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<td>6 points</td>
<td>6 points</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL ESTIMATED POINTS</strong></td>
<td>12</td>
<td>16</td>
<td>16</td>
</tr>
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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) may be substituted for this purpose.

2. Students must complete a minimum of 128 points to graduate.

3. See page 9; not required for Combined Plan students.

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 career in mechanical engineering. The program in mechanical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET, 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 6 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 topics course APMA E2101. In addition, such students are encouraged to take a course in partial differential equations (APMA E3102 or E4400) as well as a course in numerical methods (APMA 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.). FE 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 FE licensure requires some years of experience and a second examination, which tests knowledge gained in engineering practice. For more information, please see http://nces.org/exams/fe-exams/.

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...
The Integrated B.S./M.S. degree program is open to a qualified group of Columbia juniors and makes possible the following of both the B.S. and M.S. degree in an integrated fashion. Benefits of this program include 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 simplification of the 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 3.5 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 junior and senior 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 to seniors to apply toward their M.S. degree and the advanced courses that will be taken in this program do not need to have the exact prerequisites completed as an undergraduate. Other advantages include the opportunity to be a part of a stronger community and creating a streamlined set of courses more possible. Additional benefits include simplification of the 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.

GRA DUATE PROGRAMS

The Department of Mechanical Engineering offers two doctoral degrees: Doctor of Philosophy (Ph.D.) and Doctor of Engineering Science (Eng.Sci.D.), and the Master of Science degree. The Ph.D. degree is conferred by the Graduate School of Arts and Science, and the Eng.Sci.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. Ph.D. candidates are strongly encouraged to complete ENGI E5501-6004 and should consult their program for 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 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 discernable focus. In consultation with his/her adviser an M.S. student can develop a focus specifically tailored to his/her 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, mechanical design, 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 4000-level courses, chosen in consultation with an adviser. At least one of the 4000-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.

3. Out-of-department study is encouraged, must be in consultation with advisor.

4. At least five course must be in Mechanical Engineering.

Rather than selecting the standard option, students can select an elective specialization in either energy systems, micro/nanoscale engineering, or robotics and control. The required courses for a specialization are identified to those of the standard track, with one exception: students have the ability to choose at least one course from a list determined by an adviser in consultation with an advisory committee. The currently available elective specializations are listed below.

M.S. in Mechanical Engineering with Concentration in Energy Systems

Advisors: Professors James Hone and P. James Schuck

The elective 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-scale sizes. Application areas include MEMS, microfluids, thermodynamic systems, and carbon nanotubes.

Requirements: While satisfying the general mechanical engineering requirements, take at least five courses from the following list:

MECE E4201: Energy infrastructure planning
MECE E4211: Energy: sources and conversion
MECE E4212: Advanced energy materials
MECH E4201: Turbomachinery
MECH E4203: Mechanics and thermodynamics
MECH E4211: Solar thermal engineering
MECE E6100: Model of heat and mass transfer in green buildings
ELEN E4310: Intro to combustion
ELEN E4330: Thermalfluid systems design
MECE E6102: Advanced heat transfer and fluid dynamics
MECE E6103: Compressible flow
MECE E6104: Case studies in computational fluid dynamics
MECE E6105: Advanced heat transfer
EASE E6108: Carbon sequestration

*One 3-point research course can be counted in lieu of up to 3 points of approved coursework. 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

Advisors: Professors James Hone and P. James Schuck

The elective 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-scale sizes. Application areas include MEMS, microfluids, thermodynamic systems, and carbon nanotubes.

Requirements: While satisfying the general mechanical engineering requirements, take at least five courses from the following list:

MECE E4211: Advanced energy materials
MECE E4212: BioMEMS
MECH E4201: Turbomachinery
MECE E5501: Microfluidics
MECE E5502: Micro and nanoscale manufacturing laboratory
MECE E5502: Nano/microscale thermal transport processes
MECE E5509: Small scale mechanical behavior
ELEN E4503: Sensors, actuators, and mechatronic systems
ENME E6645: Device nanofabrication
BMEN E4590: BioMEMS: cellular and molecular biomechanics
MSE E4900: Nanotechnology

M.S. in Mechanical Engineering with Concentration in Robotics and Control

Advisors: Professors Sumit Agrawal, Mati Coccia, Ho Lip Lim, 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 customized for joining established companies, information-age dominant players investing heavily in this field, or the next wave of startups 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 career in related areas, in both academia and industry.

Candidates for the M.S. with specialization in Robotics and Control should simultaneously satisfy these two sets of requirements:

Take at least five courses from the list below during their M.S. courses taken during undergraduate studies do not count.

Courses in the Mechanical Engineering Department

ELEN E4493: Introduction to control theory
ELEN E4494: Optimization and control
ELEN E4502: Nanorobotic systems
ELEN E4503: Sensors, actuators, and mechatronic systems
ELEN E4605: Autonomous systems
MECE E4201: Energy infrastructure planning
MECE E4211: Energy: sources and conversion
MECE E4212: Advanced energy materials
MECH E4201: Turbomachinery
MECH E4203: Mechanics and thermodynamics
MECH E4211: Solar thermal engineering
MECE E6100: Model of heat and mass transfer in green buildings
ELEN E4310: Intro to combustion
ELEN E4330: Thermalfluid systems design
MECE E6102: Advanced heat transfer and fluid dynamics
MECE E6103: Compressible flow
MECE E6104: Case studies in computational fluid dynamics
MECE E6105: Advanced heat transfer
EASE E6108: Carbon sequestration

*One 3-point research course can be counted in lieu of up to 3 points of approved coursework. If the research is approved by the student’s adviser and is energy related.

Examples of suitable APMA courses are: APMA E4001 Principles of applied mathematics; APMA E4301y. Introduction to numerical methods; APMA E4301x Numerical methods for partial differential equations; and APMA E4204x Functions for complex variables.

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 will be awarded the Master of Science degree while pursuing their doctoral degree.

Doctoral candidates are expected to attain a level of expertise in the area of mechanical engineering and must therefore choose a field and take the most courses in that field. Candidates are assigned a faculty adviser whose task is to help choose an area of specialization, to provide general advice on academic matters, and monitor academic performance. Candidates also choose a3 faculty member in the pertinent area of specialization to serve as their research advisor. This advisor helps select a research problem and supervises the research, writing, and defense of the dissertation.

Program Requirements

1. 30 credits beyond master’s degree
2. GPA of 3.5 or better in graduate courses
3. 4 semesters of graduate seminar
4. Completion of all milestones

See me.columbia.edu/doctoral-program for more information.
MECE E4050x Multi-disciplinary design and optimization. 3 pts. Lect: 3. Professor Ateshian. A study of current design generating techniques and development of design criteria. Review of fundamental concepts and methods for multi-disciplinary design and optimization. Application to real-world design and development problems.


MECE E4052x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4053x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4054x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4055x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4056x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4057x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4058x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4059x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4060x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4061x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4062x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4063x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.

MECE E4064x Advanced microprocessors and computer architecture. 3 pts. Lect: 3. Professor Abeille. Advanced microprocessors and computer architecture. Current microprocessors and computer architectures, instruction set architecture, execution unit design, computer microarchitecture, and optimization methods.
MECE E4990x and y Fieldwork
1 pt. Professor Lipson
Prerequisites: Instructor’s permission. Written permission by ME: for graduate students who wish to take a course work experience as part of their program of study. The course of study as determined by the instructor. Written application must be made prior to registration and approval secured for proposed study program. Final report required. May not be taken for pass/fail credit or audit.

MECE E4995x or y Internship
3 pts. 3rd. Professor Avellaneda
Prerequisites: MATH UN3007 or MATH E3100, E3111. Variables, inter/intra-organizational properties of systems. Potential flow. Hands-on projects in a variety of areas.

MECE E5100x Advanced mechanics of fluids
3 pts. 3rd. Professor Domenico

MECE E5101x Advanced research in computational fluid mechanics
3 pts. 3rd. Professor Domenico
Prerequisites: MECE E4100x and E4111. Fundamental analysis of non-Newtonian flow and its applications for problems involving complex geometries and high-performance computing. Hands-on projects in a variety of areas.

MECE E6100x Advanced mechanics of fluids
3 pts. 3rd. Professor Domenico

MECE E6105 Advanced Methods of Fluid Dynamics
3 pts. 3rd. Professor Schuck

MECE E6106x Advanced Fluid Dynamics
3 pts. 3rd. Professor Ateshian

MECE E6107 Advanced Mechanics of Fluids
3 pts. 3rd. Professor Myers

MECE E6120x Computational Fluid Dynamics
3 pts. 3rd. Professor Domenico

MECE E6125x Advanced Computational Fluid Dynamics
3 pts. 3rd. Professor Myers

MECE E6130x Advanced Fluid Mechanics
3 pts. 3rd. Professor Myers

MECE E6140 Advanced Thermodynamics
3 pts. 3rd. Professor Schuck

MECE E6150 Advanced Methods of Fluid Dynamics
3 pts. 3rd. Professor Myers

MECE E6180 Advanced fluid mechanics
3 pts. 3rd. Professor Schuck

MECE E6400x Advanced machine dynamics
3 pts. 3rd. Professor Chait

MECE E6412x Introduction to the theory of elasticity, I and II
3 pts. 3rd. Professor Myers

MECE E6420x Vibrations in machines, I
3 pts. 3rd. Professor Myers

MECE E6421x Vibrations in machines, II
3 pts. 3rd. Professor Myers

MEBM E6310x-ME6311y Mixture theories for multiphase flows
3 pts. 3rd. Professor Agrawal

MECE E6710y Nanofabrication laboratory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite: ELEN E5943 or instructor’s permission. Laboratory in techniques for fabrication at the nanometer scale. Electron-beam lithography, Plasma etching and X-ray nanofabrication. Thin film deposition. Self-assembly and “bottom up” nanofabrication. Fabrication and testing of complete nanodevices. A lab fee of $300 is required.

MECE E6720x Nano/microwave thermal transport process

MECE E8100y or E8107y 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 advisor. Must obtain permission from a thesis advisor 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 advisor will assign a single grade. Students must use a department-recommended format for thesis writing.

MECE E8105y Advanced topics in fluid mechanics
Prerequisites: MECE E6102. 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 E8107y Advanced continuum biomechanics
3 pts. Lect: 2. Professor Myars.
Prerequisites: 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 Prîvîn-Endresen 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 constitutive equations.

EEME E8601y Advanced topics in control theory
Prerequisites: EEME E6601 and E4601 or instructor’s permission. May be taken more than once, since the content changes from year to year, electing different topics from control theory such as learning and repetitive control, adaptive control, systems identification, Kalman filtering, etc.

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 doctorate may be required to register for this course every term after his/her coursework has been completed and until the dissertation has been accepted.
MINOR IN ART HISTORY

1–7. Seven courses in art history, covering four of the following areas: (a) ancient Mediterranean, (b) medieval Europe, (c) Renaissance and Baroque, (d, 18th, 19th, and 20th century, and (e) non-Western

MINOR IN COMPARATIVE 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 advisor.

1. BIOL UN2005: Introduction to biology, I
2. BIOL UN2006: Introduction to biology, II
3. BMEN E3010: Biomedical engineering, I
4. BMEN E3020: Biomedical engineering, II
5. BMEN E4001: Quantitative physiology, I
6. BMEN E4002: Quantitative physiology, II

MINOR IN BIOlogical ENGINEERING

No substitutions or changes of any kind from the approved minors are permitted (see lists below). No appeal or 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 pass/fail may be counted for a minor. Minimum GPA for the minor is 2.0.

ENGINEERING 2020–2021
4–5. Four of the following courses: MECE E3305: Introduction to mechanics of fluids or ENME UN3132: Fluid mechanics or MECE E3110: Transport phenomena, I or EAE 4300: Air pollution and chemical engineering or CIEE E4163: Modeling

MINOR IN ENGINEERING

1. Any five courses in the English Department with no distribution or seminar requirement. Transfer or study-abroad credits may not be applied.

Note: Electives may be taken only after the completion of both ENME E3113 and ENME E3114, with the exception of UN2257 and UN105, which may be taken after completion of UN105. 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 Engineering Bulletin for course descriptions and complete lists of prerequisites.

2. ENME E3113: Intro to electrical engineering (3.5) (May be replaced by a similar course or roughly equivalent experience)

Note: Not available to computer engineering majors.

MINOR IN MECHANICAL ENGINEERING

2. ENME E3105: Intro to mechanics of fluids (3)

Note: For engineering students taking MUSI UN1002: Fundamentals of music or MUSI UN1202: History of Western music, II (3)

1. MINOR IN ENVIRONMENTAL ENGINEERING

Note: Students must successfully place out of MUSI UN1002: Fundamentals of music (3.0 points).

MINOR IN MECHANICAL ENGINEERING

2. MUSI UN2168: Opera (3)

MINOR IN MUSICAL PERFORMANCE

1. MUSI UN1002: Fundamentals of music (3.0 points)

3. Five courses, to be chosen with the approval of the full-time advisor in the respective Undergraduate Studies, no elementary or intermediate language courses may be counted.

MINOR IN MUSIC

1. MUSI UN1202: History of Western music, II (3)

4. Any two electives at the 3000 or 4000 level. See also the Engineering-approved nontechnical electives in music (page 10).

Note: In addition to the required courses, students majoring in operations research and its concentrations (EIM) or IEOR must minor in industrial engineering must take three additional industrial engineering courses that are not used to satisfy the requirements of their major.

1. ECON GU4321: Accounting and finance (3)

4. Electives: Two IEOR courses of interest and approved by a faculty advisor

Note: 3–5. Five courses, to be chosen with the approval of the full-time advisor in the respective Undergraduate Studies, no elementary or intermediate language courses may be counted.

MINOR IN MUSICAL PERFORMANCE

1. MUSI UN1105: Principles of economics (4)

2. ECON UN2012: Introduction to economic behavior (3)

1. MUSI UN1002: Fundamentals of music (3.0 points)

MINOR IN COMPARELIT

3. ECON GU4415: Advanced econometrics (3)

Note: Note: Students must successfully place out of MUSI UN1002: Fundamentals of music (3.0 points).
MINOR IN OPERATIONS RESEARCH

1. IEOR E3506: Probability for engineers (4)
   or STAT GU4001: Intro to probability and
   statistics (3)
2. IEOR E3106: Stochastic systems and
   applications (3)
3. IEOR E3036: Foundations of optimization (4)
4. IEOR E3040: Simulation modeling and
   analysis (4)

5-6. Electives: Two IEOR courses (6 pts) of
   interest and approved by a faculty adviser.1
   IEOR E3802: 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 at the 2000-level 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
Non-technical Courses.

Note: Please be aware that some
philosophy courses may not count as
non-technical electives.

MINOR IN POLITICAL SCIENCE

1-2. Two of the following courses:
   POLS UN1001: Intro to American govt and
elections (3)
POLS UN1001: Intro to comparative politics (3)
POLS UN1001: International politics (3)

3-5. Any three courses in the Political Science
Department with no distribution requirement;
total 9 points

MINOR IN PSYCHOLOGY

Minimum: 15 points
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 UN1010: Mind, brain, and behavior (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 3000 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 UN1111: Intro to statistics
   (w/o calculus) (3)
2. STAT UN1202: App statistical computing
   (3)
3. STAT UN1203: App linear regression
   analysis (3)
4. STAT UN1204: App categorical data
   analysis (3)
5. STAT UN3105: Applied statistical methods
   (3)
6. STAT UN3106: Applied data mining
   (3)

Notes:
• The curriculum is designed for students
   seeking practical training in applied
   statistics; students seeking a foundation
   for advanced work in probability and
   statistics should consider substituting
   UN3203, UN5204, UN5205, and
   GR5207.
• Students may, with permission of the
   Director of Undergraduate Studies
   in Statistics, substitute for courses.
   Students may count up to two courses
   toward both the Statistics minor and
   another Engineering major.

MINOR IN SUSTAINABLE ENGINEERING

Total of six courses from the following
lists required with no substitutions
allowed:
1-4. Four of the following courses:
   EAEE E2310: Alternative energy sources (3)
The social needs that elicited new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are emphasized as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking. Principles that are not prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective.

ENGI 49100y Research to revenue 3 pts. Lect. Professors Liu and Toteb. An interdisciplinary course with Columbia Business School that trains engineering and business students to identify and pursue innovation opportunities that rely on intellectual property, coming out of academic research. Idea generation, market research, product development, and financing. Teams develop and present business models for a technological invention. This course has limited enrollment by application and is open to advanced undergraduate students and graduate students. Consult with department for questions on fulfillment of technical elective requirement.

ORCA E250xx or y Foundations of data science 3 pts. Lect. Professor Zhang. Prerequisites: Calculus I and II, 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? Teaching critical concepts and skills in computer programming, statistical inference and machine learning, this course is hands-on and analysis of real-world datasets such as economic data, document collections, geographical data, and social networks. At least one course in computer science will address a problem relevant to New York City.

EEHS E3930y History of telecommunications: from the telegraph to the internet 3 pts. Lect. A. Historical development of telecommunications from the telegraphy of the mid-1850s to 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. In the social realities that elicited new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are emphasized as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking. Principles that are not prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective.

ENGI 49100y Research to revenue 3 pts. Lect. Professors Liu and Toteb. An interdisciplinary course with Columbia Business School that trains engineering and business students to identify and pursue innovation opportunities that rely on intellectual property, coming out of academic research. Idea generation, market research, product development, and financing. Teams develop and present business models for a technological invention. This course has limited enrollment by application and is open to advanced undergraduate students and graduate students. Consult with department for questions on fulfillment of technical elective requirement.

ORCA E450xx or y Foundations of data science 3 pts. Lect. Professor Zhang. Prerequisites: Calculus I and II, some familiarity with programming. Introduction to data science. Perspectives in inferential thinking, computational thinking, real-world applications. Given data arising from some real-world phenomenon, how does one analyze that data so as to understand that phenomenon? Teaching critical concepts and skills in computer programming, statistical inference and machine learning, this course is hands-on and analysis of real-world datasets such as economic data, document collections, geographical data, and social networks. At least one course in computer science will address a problem relevant to New York City.

EEHS E3930y History of telecommunications: from the telegraph to the internet 3 pts. Lect. A. Historical development of telecommunications from the telegraphy of the mid-1850s to 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. In the social realities that elicited new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are emphasized as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking. Principles that are not prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective.

ENGI 49100y Research to revenue 3 pts. Lect. Professor Liu and Toteb. An interdisciplinary course with Columbia Business School that trains engineering and business students to identify and pursue innovation opportunities that rely on intellectual property, coming out of academic research. Idea generation, market research, product development, and financing. Teams develop and present business models for a technological invention. This course has limited enrollment by application and is open to advanced undergraduate students and graduate students. Consult with department for questions on fulfillment of technical elective requirement.

COSA E90xx and y Data Science Doctoral Seminar 1 pts. Professor Blais. Prerequisites and Concerns: Faculty approval. Course required for all Data Science Doctoral Students. Others by faculty approval. The Data Science Doctoral Seminar is a 1-credit course that meets weekly. The purpose is to expose the doctoral students to a breadth of ideas in data science across disciplinary domains. The syllabus continues guest lectures from academic data scientists in the greater NYC area and faculty at Columbia, along with a selection of related readings, chosen by the guest lecturers. As part of this seminar, students will be expected to engage in open discussion about the topics and readings covered in class as well as discuss how topics apply to their own respective research areas.

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.
GRADUATE CAREER PLACEMENT

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.

Gerald Contiangco
Industrial Engineering and Operations Research (BA)

Ivy Elkins
Computer Science

David Fitzgerald
Industrial Engineering and Operations Research (OR)

Kristen Henlin
Applied Physics, Applied Mathematics, Material Science and Engineering; Biomedical Engineering

John Hyde
Data Science

Mercedes Kriesel
Industrial Engineering and Operations Research (FE)

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

ENGLISH COMMUNICATION COURSES

M.S. Courses

ENGI E5000x, y, and s Workplace communication in English
ENGI E5001x, y, and s Professional presentation in English
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. Course fee for ENGI E5000 is $350.

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 PhD and MS to PhD track students. Grading is Pass/D/Fail.

ENGI E7101x and y Great presentations

0 pts. The PDL Instructional Team. Not offered in 2020–2021.

Hands-on, practice intensive course focuses on important elements of excellent formal presentations. Fundamental principles discussed and practiced in class can be applied in a variety of contexts including the short research talk, a lab talk, the formal conference presentation, a poster presentation, a job talk, an interview, a class presentation.
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 classes. It is accomplished by following the procedures announced in advance of each registration period. It is accomplished by following the procedures announced in advance of each registration period by the Registrar. Students should consult the Registrar’s bulletin, the 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’s payment system to report their Social Security number at the time of admission. Newly admitted students who do not have a Social Security number must obtain one in advance of their first registration.

University Regulations
Each person whose enrollment has been completed is considered a student of the University during the term for which he or she is enrolled. 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 copies of the sponsorship letter.

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 semester credits per term. However, in order to complete the degree, students must be averaging 16 points per term. Students may not register for point loads greater than 21 points per term without approval from the Committee on Academic Standards. To complete the Bachelor of Science degree, a student must complete the courses prescribed in a faculty-approved major program (or faculty-approved 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, as noted below.

Registration and Satisfactory Progress
Undergraduate students 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 designated by the departments so as to meet the ABET criteria.

Changes in Registration
An undergraduate student who wishes to drop or add courses or to make other changes in his or her program of study after the change of program period must obtain the approval of his or her CSA adviser. A student who wishes to drop or add a course in his or her major must also obtain department approval. The deadline for making program changes in each term is shown in the Intraschool 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 Standards. 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 been approved to 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.

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 of University Examination Schedule is available online and is confirmed by
Grades of P, INC, D, poor but passing; F, failure (a final examination for the course is 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.

The mark of MU (make-up examination): given to a student who has failed the final examination for a course but who has been granted the privilege of taking a second examination in an effort to improve his or her 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 his or her performance on the final examination, and when, in the instructor's judgment, the make-up examination is essential.

The mark of MU (incomplete): given to students who have failed the final examination, but who have completed the major portion of the course and who have been granted the privilege of taking an examination a special examination administered as soon as the instructor can schedule it. The mark of MU may be given only in graduate research courses for the mark of MU must be made by the last day to change a course grading option. A course that has been taken for credit may not be repeated later for examination credit and cannot be uncovered under any circumstances. The mark of MU does not count toward degree requirements for graduate students. The mark of MU is automatically given in Doctoral Research Instruction courses.

The mark of 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. The mark of 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 requesting an IN grade must gain permission from both the Committee on Academic Standing (CAS) and the instructor. Graduate students should contact their instructor. If granted, an IN grade 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.

The mark of UC (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. The mark of CP (credit pending) is given only in graduate research courses in which study 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.

The mark of MU (make-up examination): given to a student who has failed the final examination for a course but who has been granted the privilege of taking a second examination in an effort to improve his or her 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 his or her performance on the final examination, and when, in the instructor's judgment, the make-up examination is essential.

The mark of MU (incomplete): given to students who have failed the final examination, but who have completed the major portion of the course and who have been granted the privilege of taking an examination.
The courses that the student must take will be determined by the Undergraduate Committee of Academic Standing, in consultation with 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 in effect 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 on Probation if they fail to meet the minimum requirements as stated in their sanction letter.

Possible academic sanctions include:

- Strict Probation: Students who have already probation and fail to meet the minimum requirements as stated in their sanction letter, and are below the minimum expectations. This sanction is typically applied when there are signs of severe academic difficulty.
- Suspension/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.
- Deferments: The decision to suspend or dismiss a student will be made by the Committee on Academic Standing in the Barnick Center for Student Advising and the Dean’s Office in 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 in North America. 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.

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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 an academic department prior to and returning from an approved voluntary personal leave of absence. The deadline to request a VPLA for a given term is the last day to drop classes during that term. VPLA 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 fact that the student was on leave will not appear on the student’s transcript. The date of the withdrawal will also appear on the transcript. If the leave begins prior to the drop deadline, then the specific coursework in which the student is enrolled will be deleted from the student's record. 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 next 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 he or she has returned to Columbia Engineering following a one-term personal leave of absence which 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. The deadlines for petitioning a return from a voluntary personal leave for graduate students are June 1 for the fall semester and November 1 for the spring semester. 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 fact that the student was enrolled for the semester and withdrew will be recorded on the student’s transcript. The date of the withdrawal will also appear on the transcript. If the leave begins prior to the drop deadline, then the specific coursework in which the student is enrolled will be deleted from the student's record. 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 next 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.

VOLUNTARY LEAVE OF ABSENCE POLICY

Please refer to the Leave of Absence Policy in Essential Policies for the Columbia Community (facets.columbia.edu) for recent updates regarding leave for military duty.

LEAVE FOR MILITARY DUTY

Please refer to the Military Leave of Absence Policy in Essential Policies for the Columbia Community (facets.columbia.edu) for recent updates regarding leave for military duty.

LEAVE OF ABSENCE DUE TO MILITARY SERVICE

Students seeking readmission must submit evidence that they have achieved the purposes for which they left. Consequently, specific readmission procedures are determined by the Departmental Adviser 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 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 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 matter a great deal of written work while at 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: term papers, seminar and laboratory reports, and essays of different lengths. These papers play a major role in course performance, but more important, 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
pursposes of completing assignments for submission. 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.

The most prevalent forms of plagiarism involves students using information from the internet without properly attributing the 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 are available to help as questions arise about proper citations, references, and the appropriateness of group work on assignments. Another option is to connect with Research Librarians for citation management workshops. Information on these workshops is posted online on the Columbia Libraries website. The Director of Academic Integrity in Suite 601 of Lerner Hall. Graduate students should consult or meet their advisor in 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 or Disciplinary hearing process may result in more serious consequences.

Types of academic integrity violations:

• Academic Dishonesty, Facilitation of: assisting another student in violation of academic integrity is prohibited. This may include but is not limited to selling 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, test, quiz, or assignment outside the time constraints imposed, the unauthorized use of prescription medication to enhance academic performance, and altering an examination or assignment to aid an instructor for rewarding.

• 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, and projects.

• Dishonesty: fabrication, forgery, or misrepresentation of information to any University official in an effort to gain an unfair 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, fabricating work, 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, honors 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: any 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.

• Text Conditions: violations of combined 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 Residential Life. Some 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 allegations, picking, and other mass demonstrations, the Rules of University Conduct outlines procedures.

Student Conduct and Community Standards is responsible for administering the Dean’s Discipline disciplinary process for all disciplinary affairs concerning students that are not related to 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 and, as a result, is not meant to be an adversarial or legal process. 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 related to academic misconduct. The Dean’s Discipline process is not meant to be an adversarial or legal process. 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.

Students are referred to the Standards and Discipline handbook and the comprehensive list of policies and expectations available on the Students Conduct and Community Standards website (studentconduct@columbia.edu). For more information about the discipline process for graduate students, please visit the Office of Graduate Student Affairs.
Directory of University Resources
Mathematics
410 Mathematics, MC 4426
212-854-2432

Physics
704 Pupin, Mail Code 5255
212-854-3348

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: 101 Bard Hall
50 Haven Avenue
212-304-7026

PUBLIC SAFETY
111 Low Library, MC 4301
212-854-2797 (24 hours a day)
publicsafety@columbia.edu
publicsafety.columbia.edu

Campus Emergencies:
212-854-5555 (4-5555)

Escort Service:
212-854-SAFE (4-7233)

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
205 Kent, MC 9202
212-854-4400
ssc@columbia.edu
ssc.columbia.edu

UNIVERSITY LIFE
212-854-0411
UniversityLife@columbia.edu
universitylife.columbia.edu

ENGINEERING 2020–2021
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