COLUMBIA ENGINEERING

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BULLETIN 2024–2025

Mission

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

A MESSAGE FROM THE DEAN

Each year, Columbia engineers pursue a robust course of study of great depth and breadth, one that prepares them for a variety of pursuits in engineering and applied science, as well as many other fields and industries.

Columbia Engineering has a proud history of innovation that has made a profound impact on our daily lives. From mass production of antibiotics, New York City's first subway line, and the earliest computer systems, our faculty and alumni have contributed technical breakthroughs that changed our world forever.

Today, we are equally committed to teaching, research, and translation that will better society and bring our engineering for humanity vision to life. Our students are a central part of this mission. Coming to Columbia Engineering means choosing a course of study that will broaden and deepen your knowledge, skills, and capacity. Combining technical prowess with courses in the liberal arts from Columbia's Core prepares students to be 21st Century Engineers. You will learn to question, to investigate, and to think deeply about how technology intersects with society.

Our programs and courses cultivate students who will be leaders in whatever field they choose to pursue and make a contribution to their communities, to the nation, and to the world.

Here at Columbia, faculty and students work together, collaborating at the intersection of disciplines to address the most exciting and challenging questions of our time. With the help of staff, advisors, state-of-the-art facilities and labs, and countless resources, students receive the support they need to succeed.

I encourage all of you to pursue the many possibilities available to you here at Columbia in the City of New York.

With best wishes for the academic year,

Shih-Fu Chang
Dean, Columbia Engineering
Morris A. and Alma Schapiro Professor

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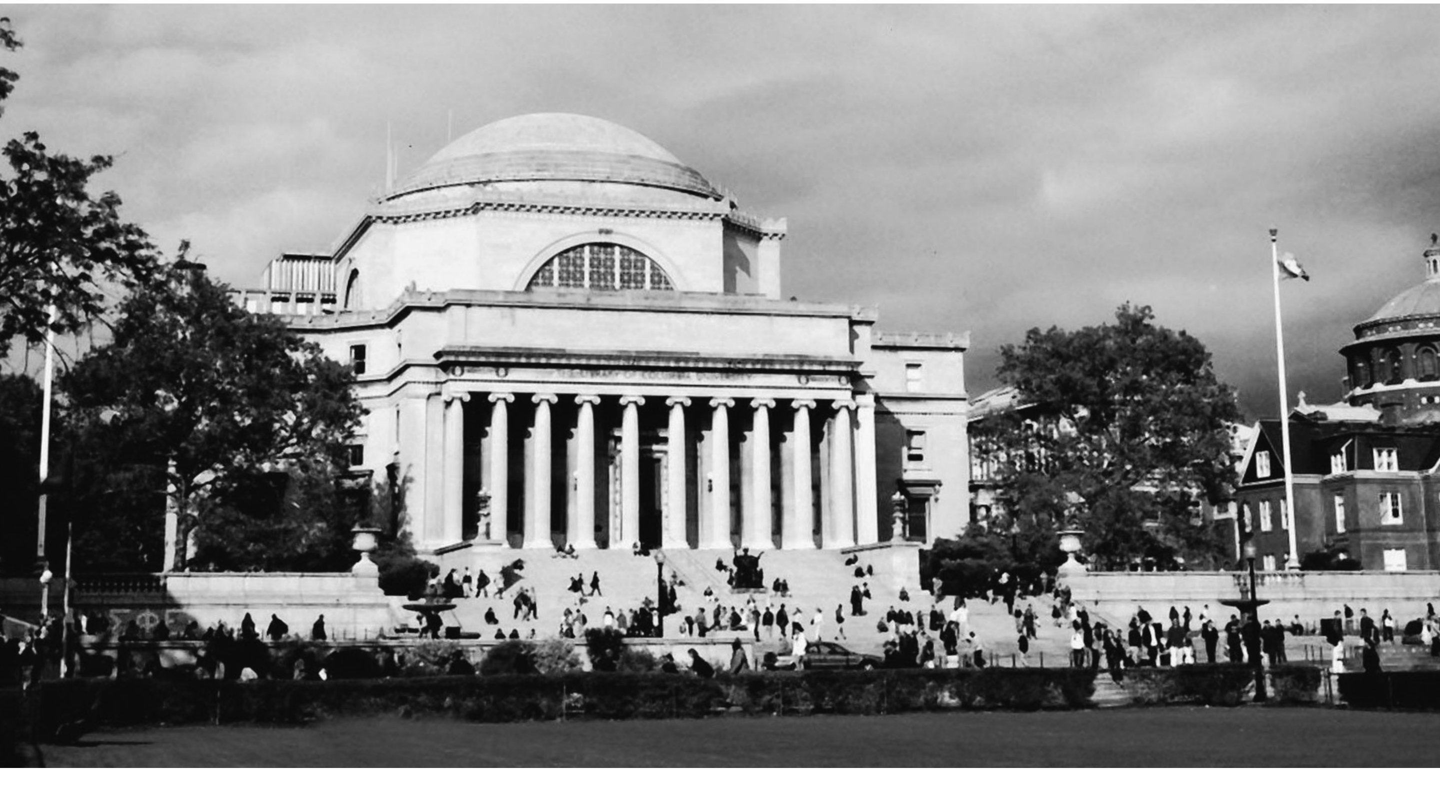
About the School and University



A COLONIAL CHARTER

Since its founding in 1754, as King's College, Columbia University has always been an institution both of and for the City of New York. And it has always been an institution of and for engineers. In its original charter, the College stated that it would teach, among other things, "the arts of Number and Measuring, of Surveying and Navigation, . . . the knowledge of . . . Meteors, Stones, Mines and Minerals, Plants and Animals, and everything useful for the Comfort, the Convenience and Elegance of Life."

THE GILDED AGE

As the city grew, so did the School. King's College was rechartered as Columbia College in 1784 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. Opened in 1904, the subway's electric cars took passengers from City Hall to Brooklyn, the Bronx, and the newly renamed and relocated Columbia University in Morningside Heights.

A MODERN SCHOOL FOR MODERN TIMES

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

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

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

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

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

TECHNOLOGY AND BEYOND

Today, The Fu Foundation School of Engineering and Applied Science, as it was named in 1997, continues to

provide leadership for scientific and educational advances. Even Joseph Engelberger, Class of 1946, the father of modern robotics, could not have anticipated the revolutionary speed with which cumbersome and expensive "big science" computers would shrink to the size of a wallet.

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

NEW RESEARCH FRONTIERS

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

Increasingly, the inventions emerging from Columbia Engineering are developed in collaboration with other researchers, expanding the potential applications for their important work. Programs such as the COSMOS Wireless Testbed, the Columbia IBM-Center for Blockchain and Data Transparency, the Columbia Center of AI Technology, the Columbia Electrochemical Energy Center, and the CS3 Center for Smart Streetscapes are strengthening interdisciplinary capacity and fostering an entrepreneurial and inventive energy within the School. Some of these programs and centers have helped prepare ideas for commercialization, including personalized robotics for use in physical rehabilitation and an implantable device that acts as a minimally-invasive glucose sensor for diabetic patients.

ENTREPRENEURSHIP

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

Entrepreneurship remains an important central educational theme at Columbia Engineering. The School offers a range of programs and a 15-credit, interdisciplinary minor in entrepreneurship, as well as a dual degree program with Columbia Business School (CBS), the MBAxMS, which consists of a MBA from CBS and an Executive MS in Engineering and Applied Science from Columbia Engineering. The School also provides a four-year entrepreneurship experience for all interested Columbia Engineering students, regardless of major.

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

A FORWARD-LOOKING TRADITION

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

A COLLEGE WITHIN THE UNIVERSITY

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

THE NEW YORK ADVANTAGE

Besides the faculty, the single greatest resource for students is without doubt the City of New York. Within easy reach by walking, bus, subway, or taxi, New York's broad range of social, cultural, and business communities offer an 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, New York is the cultural crossroads of the world.

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

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

THE UNIVERSITY AT LARGE

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

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

THE MORNINGSIDE HEIGHTS CAMPUS

Columbia Engineering is located on Columbia's Morningside campus. One of the handsomest urban institutions in the country, the 13.1 million gross square feet (gsf) of the Morningside campus comprise more than 200 buildings of housing; off-campus apartments and commercial buildings; recreation and research facilities; centers for the humanities and social and pure sciences; and professional schools in architecture, business, the fine arts, journalism, law, and many other fields.

MANHATTANVILLE CAMPUS

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

COLUMBIA ENGINEERING

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

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

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

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

The Makerspace

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

Carleton Commons

Located on the fourth floor (campus level) of the Mudd Building, Carleton Commons and Blue Java Café/Chef Don's Pizza 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.

Columbia Engineering Computing Facilities

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

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

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

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

Undergraduate Studies

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The undergraduate programs at Columbia Engineering not only are academically exciting and technically innovative but also lead into a wide range of career paths for the educated citizen of the twenty-first century. Whether you want to become a professional engineer, work in industry or government, or plan to pursue a career in the physical and social sciences, medicine, law, business, or education, Columbia Engineering will provide you with an unparalleled education.

The School firmly believes that students gain the most when engineering is brought up front, early in the four-year curriculum. Therefore, each first-year student takes the Art of Engineering, which addresses the fundamental concepts of math and science in an engineering context, as well as nontechnical issues in professional engineering practice such as ethics and project management. 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 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 ongoing faculty research projects encompassed 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 disciplined, cultural perspective on the times they live in and the work they do.

James H. and Christine Turk Berick Center for Student Advising

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csa@columbia.edu
cc-seas.columbia.edu/csa

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

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

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

Preprofessional Advising

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

POLICY ON DEGREE REQUIREMENTS

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

THE FIRST-YEAR/SOPHOMORE PROGRAM

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

Liberal Arts Core for Columbia Engineering Students: 27-Point Nontechnical Requirement

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

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

A. Required Nontechnical Courses
(16–18 points of credit)
These courses must be taken at Columbia.

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

B. Elective Nontechnical Courses
(9–11 points of credit)
The following course listing by department specifies the Columbia College, Barnard, or Columbia Engineering courses that either fulfill or do not fulfill the nontechnical requirement.

(Professional, workshop, lab, project, scientific, studio, music instruction, and master's-level professional courses do not satisfy the 27-point nontechnical requirement.)

AFRICAN-AMERICAN STUDIES: All courses

AMERICAN STUDIES: All courses

ANCIENT STUDIES: All courses

ANTHROPOLOGY: All courses in sociocultural anthropology
All courses in archaeology except fieldwork
No courses in biological/physical anthropology [UN1010, UN1011, UN3204, UN3940, GU4147-GU4148, GU4200, GU4700]

ARCHITECTURE: No courses

ART HISTORY AND ARCHEOLOGY: All courses

ASIAN AMERICAN STUDIES: All courses

ASTRONOMY: No courses

BIOLOGICAL SCIENCES: No courses

BUSINESS: No courses

CHEMISTRY: No courses

CLASSICS: All courses

COLLOQUIA: All courses

COMPARATIVE ETHNIC STUDIES: All courses

COMPARATIVE LITERATURE AND SOCIETY: All courses

COMPUTER SCIENCE: No courses

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

DANCE: All courses except performance classes

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

EARTH AND ENVIRONMENTAL SCIENCES: No courses

EAST ASIAN LANGUAGES AND CULTURE: All courses

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

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

EDUCATION: All courses

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

ENGLISH AND COMPARATIVE LITERATURE: All courses

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

FRENCH AND ROMANCE PHILOLOGY: All courses

GERMANIC LANGUAGES: All courses

GREEK: All courses

HISTORY: All courses

HISTORY AND PHILOSOPHY OF SCIENCE: All courses

HUMAN RIGHTS: All courses

ITALIAN: All courses

JAZZ STUDIES: All courses

LATIN: All courses

LATINO STUDIES: All courses

LINGUISTICS: All courses except CLLN GU4202

MATHEMATICS: No courses

MEDIEVAL AND RENAISSANCE STUDIES:
All courses

MIDDLE EASTERN AND ASIAN LANGUAGE AND CULTURES: All courses

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

PHILOSOPHY: All courses except
UN1401 Introduction to logic
UN3411 Symbolic logic
GU4137 Nonclassical logics
GU4431 Introduction to set theory
GU4424 Modal logic
CSPH GU4801 Mathematical logic I
CSPH GU4802 Incompleteness results in logic
GU4810 Lattices and Boolean algebras
Courses in logic

PHYSICAL EDUCATION: No courses

PHYSICS: No courses

POLITICAL SCIENCE: All courses except
UN3220 Logic of collective choice
UN3704 Data analysis and statistics for political science research
UN3720 Scope and methods
GU4730 Game theory and political theory
GU4732 Research topics in game theory
GU4791 Advanced topics in quantitative research
GU4792 Advanced topics in quantitative research
GU4700 Math methods for political science
GU4765 Design and analysis of sample surveys
GU4768 Experimental research: design, analysis, and interpretation
GU4710 Principles of quantitative political research
GU4711 Analysis of political data
GU4712 Multivariate political analysis

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

RELIGION: All courses

SLAVIC LANGUAGES: All courses

SOCIOLOGY: All courses except SOCI UN3020 Social statistics

SPANISH AND PORTUGUESE: All courses

SPEECH: No courses

STATISTICS: No courses

SUSTAINABLE DEVELOPMENT: No courses

URBAN STUDIES: All courses

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

WOMEN AND GENDER STUDIES: All courses

Music Instruction Courses

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

Visual Arts Courses

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

Technical Course Requirements

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

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

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

Professional Development

Professional-Level Courses

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

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

The courses are:

BMEN E1001x Engineering in medicine
Not offered in 2024–2025.
The present and historical role of engineering in medicine and healthcare delivery. Engineering approaches to understanding organismic and cellular function in living systems. Engineering in the diagnosis and treatment of disease. Medical imaging, medical devices: diagnostic and surgical instruments, drug delivery systems, prostheses, artificial organs. Medical informatics and organization of the healthcare system. Current trends in biomedical engineering research.

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

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

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

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

MECE E1001x Mechanical engineering: micro-machines to jumbo jets
Not offered in 2024–2025.
Corequisite(s): MATH UN1101. The role of mechanical engineering in developing many of the fundamental technological advances on which today's society depends. Topics include airplanes, automobiles, robots, and modern manufacturing methods, as well as the emerging fields of micro-electro-mechanical machines (MEMS) and nanotechnology. The physical concepts that govern the operation of these technologies will be developed from basic principles and then applied in simple design problems. Students will also be exposed to state-of-the art innovations in each case study.

Physical Education

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

The majority of the activities are offered in ten time preferences. Additionally, there are early-morning conditioning activities, Friday-only classes at Baker Athletics Complex, and special courses that utilize off-campus facilities during weekends and vacation periods. The courses offered by the department for each term are included in the online Directory of Classes, and a description of the scheduled activities for each time preference is posted on perec.columbia.edu. Students may only register for one section of physical education each term.

Advanced Placement Credit Chart

In order to receive AP credit, students must be in possession of appropriate transcripts or scores and send official score reports to Columbia.
The CEEB code is 2116.

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

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

**Columbia Engineering students with a 4 or 5 on Calculus AB or a 4 on Calculus BC must begin with MATH UN1101 (Calculus I) or MATH UN1102 (Calculus II). If a Columbia Engineering student with these scores goes directly into APMA E2000 (Multivariable Calculus), they will have to go back and complete MATH UN1102 (Calculus II). Students with A-level or IB calculus credit must start with either MATH UN1101 or MATH UN1102. They cannot self place into APMA E2000. If they start with MATH UN1101, they will not receive any advanced standing credit.

Advanced Placement

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

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

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

International Baccalaureate (IB)

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

British Advanced Level Examinations

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

Other National Systems

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

STUDY ABROAD

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

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

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

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

Eligibility Requirements

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

Finances

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

Academic Credit

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

Deadlines

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

For more information on study abroad, students should contact:

Center for Undergraduate Global Engagement
606 Kent Hall, MC 3948
1140 Amsterdam Avenue
New York, NY 10027
212-854-2559
uge@columbia.edu
uge.columbia.edu

SEAS Undergraduate Student Affairs
ask-seas@columbia.edu

COMBINED PLAN PROGRAMS

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

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

The Combined Plan Program within Columbia University

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

The Combined Plan with Other Affiliated Colleges

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

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

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

THE JUNIOR-SENIOR PROGRAMS

Students may review degree progress via DARS (Degree Audit Reporting System) as presented on Student Services Online. Required courses should be completed according to the academic charts in the department sections of the bulletin. Until they are completed, they are listed as deficiencies in the Degree Audit Report. If they are not completed according to the departmental plans, it may be necessary to complete these courses either over the summer or be carried as overload courses in later semesters.

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

Double Major

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

Major courses cannot be cross-counted between dual majors. Please consult with an Advising Dean and the respective departmental advisors to find alternative courses for duplicate requirements.

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

Tau Beta Pi

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

Undergraduate students whose scholarship places them in the top eighth of their class in their next-to-last year or in the top fifth of their class in their last college year are eligible for membership consideration. These scholastically eligible students are further considered on the basis of personal integrity, breadth of interest both inside and outside engineering, adaptability, and unselfish activity.

Benefits of membership include exclusive scholarships and fellowships. Many networking opportunities for jobs and internships are also available, with 230 collegiate chapters and more than 500,000 members in Tau Beta Pi.

Taking Graduate Courses as an Undergraduate & Advanced Standing

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 Engineering Student Affairs; and (3) the amount of graduate credit earned by an undergraduate cannot exceed 15 points. Undergraduates may not take CVN courses.

The Bachelor of Science Degree

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

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

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

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

Minors

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

In considering a minor, students must understand that not all minors are available to all students. Additionally, no class substitutions are permitted when completing a minor. 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, appears on pages 208–213.

PROGRAMS IN PREPARATION FOR OTHER PROFESSIONS

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

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

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

Premed

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

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

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

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

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

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

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

Prelaw

Students fulfilling the School of Engineering and Applied Science's curriculum are well prepared to apply to and enter professional schools of law, which generally do not require any specific prelaw coursework. Schools of law encourage undergraduate students to complete a curriculum characterized by rigorous intellectual training involving relational, syntactical, and abstract thinking. While selecting courses, keep in mind the need to hone your writing skills, your communication skills, and your capacity for logical analysis.

While engineering students may find interests in many areas of the law, for intellectual property and patent law, a science and technology background will be greatly valued, if not essential.

Urban Teaching: New York State

Initial Certification in Adolescence Education Grades 7–12 for Teachers of Mathematics and the Sciences or in Elementary Education Grades 1–6

Barnard College Education Program
335-336 Milbank Hall
3009 Broadway
New York, NY 10027
212-854-7072
education.barnard.edu

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

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

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

JOINT PROGRAMS

The 4-1 Program at Columbia College

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

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

Interested students should contact their advising dean for further information.

UNDERGRADUATE ADMISSIONS

Undergraduate Admissions
212 Hamilton Hall, MC 2807
1130 Amsterdam Avenue
New York, NY 10027
212-854-2522
ugrad-ask@columbia.edu
undergrad.admissions.columbia.edu

For information about undergraduate admissions, please visit the Undergraduate Admissions website or contact the office by phone or email.

See page 28 for information about graduate admissions, including combined undergraduate/graduate programs.

UNDERGRADUATE TUITION, FEES, AND PAYMENTS

The 2024–2025 tuition and fees are estimated. Tuition and fees are prescribed by statute and are subject to change at the discretion of the Trustees.

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

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

Students with an overdue account balance may be prohibited from registering, changing programs, or obtaining a diploma or transcripts. In the case of persistently delinquent accounts, the University may utilize the services of an attorney and/or collection agent to collect any amount past due. If a student's account is referred for collection, the student may be charged an additional amount equal to the cost of collection, including reasonable attorney's fees and expenses incurred by the University.

TUITION

Undergraduate students enrolled in The Fu Foundation School of Engineering and Applied Science pay a flat tuition charge of $34,000 per term, regardless of the number of course credits taken. Postgraduate special students and degree candidates enrolled for a ninth term are billed according to the per-point system; the per-point cost is $2,188.

MANDATORY FEES

Orientation fee: $570 (one-time charge in the first term of registration)
Student Life fee: $891 per term
Health and Related Services fee: $694 per term
International Services charge: $160 per term (international students only)
Document fee: $105 (one-time charge)

OTHER FEES

Application and late fees:

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

Books and course materials: Depends upon course

Laboratory fees: See course listings

Room and board (estimated): $17,580 for first year students

HEALTH INSURANCE

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

PERSONAL EXPENSES

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

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

LABORATORY CHARGES

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

DAMAGES

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

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

TUITION AND FEE REFUNDS

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

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

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

Percentage Refund for Withdrawal during First Nine Weeks of Term

Prorated for calendars of a different duration:

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%

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 FOR UNDERGRADUATE STUDY

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. Financial aid is available for all four undergraduate years, provided that students continue to demonstrate financial need.

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

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

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

Satisfactory Academic Progress

Columbia University complies with federal SAP regulations. To be eligible for Federal Student Aid (Federal Pell Grant, Federal SEOG, Federal Work-Study, Federal Perkins Loan, Federal Direct/PLUS loan), an otherwise eligible student must meet or exceed the SAP standards set by their school or program at the time SAP is assessed. The SAP policy may be found online at sfs.columbia.edu/central-sap-policy.

Graduate Studies

THE GRADUATE PROGRAMS

Graduate programs of study in The Fu Foundation School of Engineering and Applied Science are not formally prescribed, but are planned to meet the particular needs and interests of each individual student. Departmental requirements for each degree, which supplement the general requirements given below, appear in the sections on individual graduate programs.

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

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

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

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

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

THE MASTER OF SCIENCE DEGREE

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

While a suitable Master of Science program will necessarily emphasize some specialization, the program should be well balanced, including basic subjects of broad importance as well as theory and applications. The history of modern economic, social, and political institutions is important in engineering, and this is recognized in the prescribed undergraduate program of the School. If the candidate's undergraduate education has been largely confined to pure science and technology, a program of general studies, totaling from 6 to 8 points, may be required. Supplementary statements covering these special requirements are issued by the School's separate departments. An applicant who lacks essential training will be required to strengthen or supplement the undergraduate work by taking or repeating certain undergraduate courses before proceeding to graduate study. No graduate credit (that is, credit toward the minimum 30-point requirement for the Master of Science degree) will be allowed for such subjects. Accordingly, Master of Science programs may include from 35 to 45 points and may require three terms for completion. Doctoral research credits cannot be used toward 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.

An M.S. student may submit an application to apply and transfer to another academic program but cannot transfer earlier than the first semester of enrollment. If the student is not successful with the application process, then they must make sure requirements for the original academic program are completed.

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

The Professional Development and Leadership (PDL) program educates students to maximize performance and achieve their full potential to become engineering leaders. The core modules focus on development of professional skills and perspectives needed to succeed in a fast-changing technical climate.

M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement. This course is expected to be completed during the first two semesters of enrollment.

Professional Development Leadership Doctoral Requirement (ENGI 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 stage of the doctoral program, with a focus on the development of academic, research, and professional skills. Students will also have the opportunity to participate in small group communication workshops for doctoral students and individualized coaching tailored to their specific goals. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

Executive Master of Science in Engineering and Applied Science

Offered by Columbia Engineering, the Executive Master of Science in Engineering and Applied Science will provide students with a broad understanding of engineering science and the end-to-end product development process. It is intended for professionals who are preparing for leadership roles that need an understanding of the development process of new products (goods or services). Candidates for the Executive Master of Science in Engineering and Applied Science are required to complete a minimum of 30 graduate-level credits, which includes core courses (15 credits), electives in their concentration (12 credits in one concentration), and a capstone project that integrates their overall learning experience and prepares them to take on a significant leadership role (3 credits). M.S. students must complete the professional development and leadership course, ENGI E4000, as a graduation requirement.

The 4-2 Master of Science Program

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

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

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

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

Please contact the Office of Engineering Student Affairs. You should also contact your home institution's Combined Plan liaison for program information. You may, in addition, email questions to seasgradmit@columbia.edu.

Dual Degree Program with Columbia Business School (MBAxMS)

Columbia Business School and Columbia Engineering offer a dual degree program leading to the degrees of Master of Business Administration and Master of Science in Engineering and Applied Science. (See Executive Master of Science in Engineering and Applied Science.)

Dual Degree Program in Computer Science with the School of Journalism

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

Dual Degree Program in Industrial Engineering with Columbia Business School

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

Master of Science Program in Management Science and Engineering

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

Master of Science Program in Business Analytics

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

Master of Science in Data Science

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

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

Certificate of Professional Achievement in Data Science

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

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

Two doctoral degrees in engineering are offered by the University: the Doctor of Engineering Science, administered by The Fu Foundation School of Engineering and Applied Science, and the Doctor of Philosophy, administered by the Graduate School of Arts and Sciences. Both doctoral programs are subject to review by the Committee on Instruction of the School. Doctoral students may submit a petition to the Office of Engineering Student Affairs to change from the Eng.Sc.D. degree to the Ph.D. degree or from the Ph.D. degree to the Eng.Sc.D. degree. The petition must be submitted within the first year of enrollment in the doctoral program. Any petitions submitted after this period will not be considered. Doctoral degree status can be changed only once; students, therefore, must determine which doctoral degree program is most appropriate for their academic and professional endeavors.

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

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

For the Ph.D. Degree

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

Ph.D. candidates who have completed all six Residence Units can satisfy the continuous registration requirement and make use of various University facilities by registering for Matriculation & Facilities (M&F) for a maximum of two semesters if they are:

1. completing a degree requirement such as a language examination or qualifying examination;

2. preparing the dissertation proposal; or
3. writing or distributing the dissertation.

If a Ph.D. student is registered in courses or holds a university teaching or research appointment, the student must register for either a full Residence Unit or Extended Residence.

The term in which the dissertation distribution occurs is the last semester in which a Ph.D. student is permitted to register, even if the defense takes place in a subsequent term. Students should distribute final copies of the dissertation to defense committee members at least four weeks before the anticipated defense date to allow adequate time for committee members to review the dissertation thoroughly. The defense is expected to take place no later than two months after the distribution.

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

For the Eng.Sc.D. Degree

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

Doctoral Research Instruction

An Eng.Sc.D. candidate is required to complete 12 credits in the departmental course E9800: Doctoral research instruction in accordance with the following guidelines:

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

Completion of Requirements

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

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

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

NONDEGREE STUDENTS

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

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

The Office of Engineering Student Affairs at The Fu Foundation School of Engineering and Applied Science is integral to the School's teaching, research, and service mission and works to enhance the educational opportunities available to students. This office provides leadership for the integration of educational programs and services that enhance recruitment, retention, and quality of campus life for graduate students at Columbia Engineering. It strives to demonstrate sensitivity and concern in addressing the needs of the School's population. The office is dedicated to providing service to prospective, new, and continuing students pursuing a graduate education in engineering or applied science. See page 232.

COLUMBIA VIDEO NETWORK

Columbia Video Network
540 S. W. Mudd, MC 4719
500 West 120th Street
New York, NY 10027

212-854-6447
info@cvn.columbia.edu
cvn.columbia.edu

BACKGROUND

Columbia University's Fu Foundation School of Engineering and Applied Science established the Columbia Video Network (CVN) in 1986 to meet a growing need within the engineering community for a graduate distance education program. More than 30 years later, our part-time fully online programs provide working professionals high quality graduate engineering education in a convenient and flexible format.

PROGRAM BENEFITS

At CVN, a top-ranked Best Graduate Online Engineering Program by the 2024 *U.S. News & World Report,* students can enroll in online courses and earn graduate engineering degrees without ever having to set foot on campus. CVN courses are taught by Columbia University faculty, offering students flexibility coupled with the high-caliber teaching, resources, and standards inherent in The Fu Foundation School of Engineering and Applied Science.

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

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

PROGRAMS OF STUDY

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

Master of Science (M.S.) Degree Programs

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

Fields of Study:

- Applied Mathematics
- Applied Physics
- Biomedical Engineering
- Chemical Engineering
- Civil Engineering
- Computer Science (8 tracks)
  - Computational Biology
  - Computer Security
  - Foundations of Computer Science
  - Machine Learning
  - Natural Language Processing
  - Network Systems
  - Personalized Track
  - Software Systems
- Earth and Environmental Engineering
- Electrical Engineering
- Industrial Engineering: Systems Engineering
- Materials Science and Engineering
- Mechanical Engineering
- Operations Research: Methods in Finance

M.S. Application

The M.S. application requires a minimum cumulative undergraduate GPA of 3.0, a resume/CV, a 250-word personal/professional statement, an unofficial transcript for each university attended, three letters of recommendation, self-reported GRE General Test scores (GRE scores are valid for five years), TOEFL/IELTS scores (if applicable), and an $85 application fee. Applications are reviewed on a rolling basis, and decisions are issued no more than ten weeks after submission. Applications must be submitted via the application portal on cvn.columbia.edu.

Accepted students can begin coursework up to one year after admission into CVN.

Doctor of Engineering Science (DES) Degree Programs

The DES can be completed partially online. Students in the program can complete some of their courses online. Students also perform research on campus with a faculty adviser. Applicants must already have an M.S. in a related field prior to applying to the DES program. The DES must be completed within seven years. Applicants must have a potential faculty adviser selected prior to submitting their applications.

Fields of Study:

- Earth and Environmental Engineering
- Electrical Engineering
- Mechanical Engineering

DES Application

The DES application requires a minimum cumulative undergraduate GPA of 3.0, an M.S. in a related field, a resume/CV, a 250-word personal/professional statement, an unofficial transcript for each university attended, three letters of recommendation, self-reported GRE General Test scores (GRE scores are valid for five years), TOEFL/IELTS scores (if applicable), an $85 application fee, and the name of a prospective faculty adviser. Applications must be submitted via the application portal on cvn.columbia.edu. Applications are reviewed on a rolling basis, and decisions are issued no more than ten weeks after submission.

Certification of Professional Achievement Programs

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

Fields of Study:

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

Certification Application

The certification application requires a minimum cumulative undergraduate GPA of 3.0, a resume/CV, a 250-word personal/professional statement, an unofficial transcript for each university attended, three letters of recommendation, and an $85 application fee. Applications are reviewed on a rolling basis, and decisions are issued within a week of submission. Applications must be submitted via the application portal on cvn.columbia.edu.

Nondegree Courses

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

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

Nondegree Application

The application requires a minimum cumulative undergraduate GPA of 3.0, a resume/CV, a 250-word personal/professional statement, and unofficial transcripts from every university attended. There is no application fee. Applications are reviewed on a rolling basis, and decisions are issued within a week of submission. Applications must be submitted via the application portal on cvn.columbia.edu.

Office of Graduate Admissions
1220 S. W. Mudd, MC 4708
500 West 120th Street
New York, NY 10027

212-854-4688
seasgradmit@columbia.edu
gradengineering.columbia.edu/admissions

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: No more than 15 points of credit completed as a nondegree student may be counted toward a degree.

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

Academic integrity is the cornerstone of a university education. Failure to submit complete, accurate, and authentic application documents consistent with these instructions may result in denial or revocation of admission, cancellation of academic credit, suspension, expulsion, or eventual revocation of degree. Applicants may be required to assist admissions staff and faculty involved in admission reviews in the verification of all documents and statements made in documents submitted by students as part of the applica`tion 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 may submit the results of standardized exams. If you have taken the Graduate Record Examination (GRE) and would like to provide your scores, you may, but it is not required. Students who do not submit scores will not be penalized in the graduate admissions review process. Students who do submit scores will be required to submit official test scores should they be admitted. Students applying to the Applied Physics Ph.D. or Applied Physics MS/Ph.D. Track program may supply GRE Physics subject test scores, although it is not required. GRE general and subject test scores are valid for five years from the test administration date according to the Educational Testing Service (ETS). English language test scores are required of all applicants who received their bachelor's degree in a country in which English is not the official and widely spoken language. The Test of English as a Foreign Language (TOEFL), International English Language Testing System (IELTS), Duolingo English Test (DET), or

Pearson Test of English (PTE) scores satisfy the test requirement and are valid for two years according to the test organizations.

Applicants may be asked to participate in an interview as part of the application process.

ENGLISH PROFICIENCY

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

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

APPLICATION FEE

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

GRADUATE ADMISSION CALENDAR

Applicants are admitted twice yearly, for the fall and spring semesters.

- Fall admission application deadlines: *December 15* for Ph.D., Eng.Sc.D., and M.S. leading to Ph.D. programs and *February 15* for most M.S. only and nondegree applicants. Please visit the Office of Engineering Student Affairs website for specific M.S. only program deadlines.
- Spring admission application deadline: *October 1* for all departments and degree levels.

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

EXPRESS APPLICATION

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

BS/MS APPLICATION

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

BARNARD 4+1 PATHWAY APPLICATION

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

ONE-TERM NONDEGREE STUDENT STATUS

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

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

TRANSFER APPLICANTS

Students who wish to change program of study, either within Columbia or another institution, would need to apply for admission to the program of interest. There is no transferring between programs. Previously completed graduate-level coursework must align with Columbia Engineering Advanced Standing Policy and the degree curriculum requirements.

The 2024–2025 tuition and fees are estimated. Tuition and fees are prescribed by statute and are subject to change at the discretion of the Trustees.

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

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

Students with an overdue account balance may be prohibited from registering, changing programs, or obtaining a diploma or transcripts. In the case of persistently delinquent accounts, the University may utilize the services of an attorney and/or collection agent to collect any amount past due. If a student's account is referred for collection, the student may be charged an additional amount equal to the cost of collection, including reasonable attorney's fees and expenses incurred by the University.

TUITION

Graduate students enrolled in M.S. and Eng.Sc.D. programs pay $2,584 per credit, except when a special fee is fixed. Graduate tuition for Ph.D. students is $27, 592 per Residence Unit. The Residence Unit, full-time registration for one semester rather than for individual courses (whether or not the student is taking courses), provides the basis for tuition charges. Ph.D. students should consult the bulletin for the Graduate School of Arts and Sciences.

COMPREHENSIVE FEE/ MATRICULATION AND FACILITIES

Eng.Sc.D.

Eng.Sc.D. candidates who have completed their twelve (12) credits of Doctoral Research Instruction (see Graduate Programs), and are at the "all but dissertation" stage are assessed a Comprehensive Fee of $2,644 per term by The Fu Foundation School of Engineering and Applied Science.

PhD

The Graduate School of Arts and Sciences will assess $2,644 tuition per term for the Matriculation and Facilities (M&F) registration. Students can only register for a maximum of two semesters of M&F (see Graduate Programs).

MANDATORY FEES

University services and support fee:

- Full-time master's programs: $657 fall per term
- Part-time master's programs: $511 per term
- All other full-time programs: $602 per term
- All other part-time programs: $456 per term

Health and Related Services fee: $694 per term

International Services charge:
$160 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): $440
- Continuing full-time students (12 or more credits): $420
- First year part-time students (less than 12 credits): $220
- Continuing part-time students (less than 12 credits): $210

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

Application and late fees:

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

Books and course materials:

- Depends upon course

Laboratory fees: See course listings

IEOR master's program fee:

- Full-time master's program: $1,052
- Part-time master's program: $526

Visiting Students program fee: $526 per term

Dual MBA and Executive MS (BUEXMS) program fee : $526 per term

HEALTH INSURANCE

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

PERSONAL EXPENSES

Students should expect to incur miscellaneous personal expenses for such items as food, clothing, linen, laundry, dry cleaning, and so forth.

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

LABORATORY CHARGES

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

DAMAGES

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

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

TUITION AND FEE REFUNDS

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

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

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

Percentage Refund for Withdrawal during First Nine Weeks of Term

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

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%

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. For the Summer Change of Program period, please refer to the Summer semester academic calendar.

Please note: 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 leave of absence and withdrawals.

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

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

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

FINANCING GRADUATE EDUCATION

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

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

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

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

INSTRUCTIONS FOR FINANCIAL AID APPLICANTS

Deadlines

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

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

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

GRADUATE SCHOOL DEPARTMENTAL FUNDING

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

Institutional Grants

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

Fellowships

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

Assistantships

Teaching and research assistantships, available to doctoral students in all departments, provide tuition exemption 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 20 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 funding to complete the degree. Many international students obtain support for their educational expenses from their government, a foundation, or a private agency.

International students who apply to doctoral programs of study by the December 15 deadline and are admitted to a Columbia Engineering doctoral program are automatically considered for departmental funding (institutional grants, fellowships, and teaching and research assistantships), upon completion of the required financial aid forms referred to above. Continuing international students must preregister for classes during the preregistration period and complete an enrollment status form to be considered for departmental funding.

Most private student loan programs are restricted to U.S. citizens and permanent residents. However, international students may be eligible to apply for these domestic loan programs with a creditworthy cosigner who is a citizen or permanent resident in the United States. Depending on the loan program, you may need a valid U.S. Social Security number.

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

OTHER FINANCIAL AID—FEDERAL AND PRIVATE PROGRAMS

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

Several private student loan programs are available to both U.S. citizens and international students. These loans require that you have a good credit standing. International students may be eligible for a private loan with a creditworthy U.S. citizen or permanent resident cosigner.

Detailed information and application instructions for student loans may be found at the Office of Student Financial Planning website at sfs.columbia.edu/sfp-grad-engin.

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

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

VETERANS BENEFITS

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

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

- In person to 210 Kent Hall
- Scan and email to veterans@columbia.edu
- Fax to 212-854-2818

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

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

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

Veterans Benefits and Transition Act of 2018

In accordance with Title 38 US Code 3679 subsection (e), this school adopts the following additional provisions for any students using U.S. Department of Veterans Affairs (VA) Post 9/11 G.I. Bill® (Ch. 33) or Vocational Rehabilitation and Employment (Ch. 31) benefits, while payment to the institution is pending from the VA. This school will not:

- Prevent or delay the student's enrollment;
- Assess a late penalty fee to the student;
- Require the student to secure alternative or additional funding;
- Deny the student access to any resources available to other students who have satisfied their tuition and fee bills to the institution, including, but not limited to, access to classes, libraries, or other institutional facilities.

However, to qualify for this provision, such students may be required to:

- Produce the Certificate of Eligibility by the first day of class;
- Provide written request to be certified;
- Provide additional information needed to properly certify the enrollment as described in other institutional policies.

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

EMPLOYMENT

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

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

On-Campus Employment

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

Off-Campus Employment in New York City

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

Gainful Employment Disclosures

Programs: Engineer of Mines and Metallurgical Engineer

These programs are designed to be completed in 32 weeks.

These programs will cost $71,998 if completed within the normal time. There may be additional costs for living expenses. These costs were accurate at the time of the posting but may have changed.

Fewer than 10 students completed this program within the normal time. This number has been withheld to preserve the confidentiality of the students.

The following states/territories do not have licensure requirements for this profession: *Alabama, Alaska, American Samoa, Arizona, Arkansas, California, Colorado, Connecticut, Delaware, District of Columbia, Federated States of Micronesia, Florida, Georgia, Guam, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Marshall Islands, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, Northern Marianas, Ohio, Oklahoma, Oregon, Palau, Pennsylvania, Puerto Rico, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Utah, Vermont, Virgin Islands, Virginia, Washington, West Virginia, Wisconsin, and Wyoming.*

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

For the specific Columbia Gainful Employment Disclosures, please review them both at essential-policies.columbia.edu/files_facets/imce_shared/isclosure_CU_Template_2019_Engineer_of_Mines.pdf and essential-policies.columbia.edu/files_facets/imce_shared/sure_CU_Template_2019_Metallurgical_Engineer.pdf.

CONTACT INFORMATION

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

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

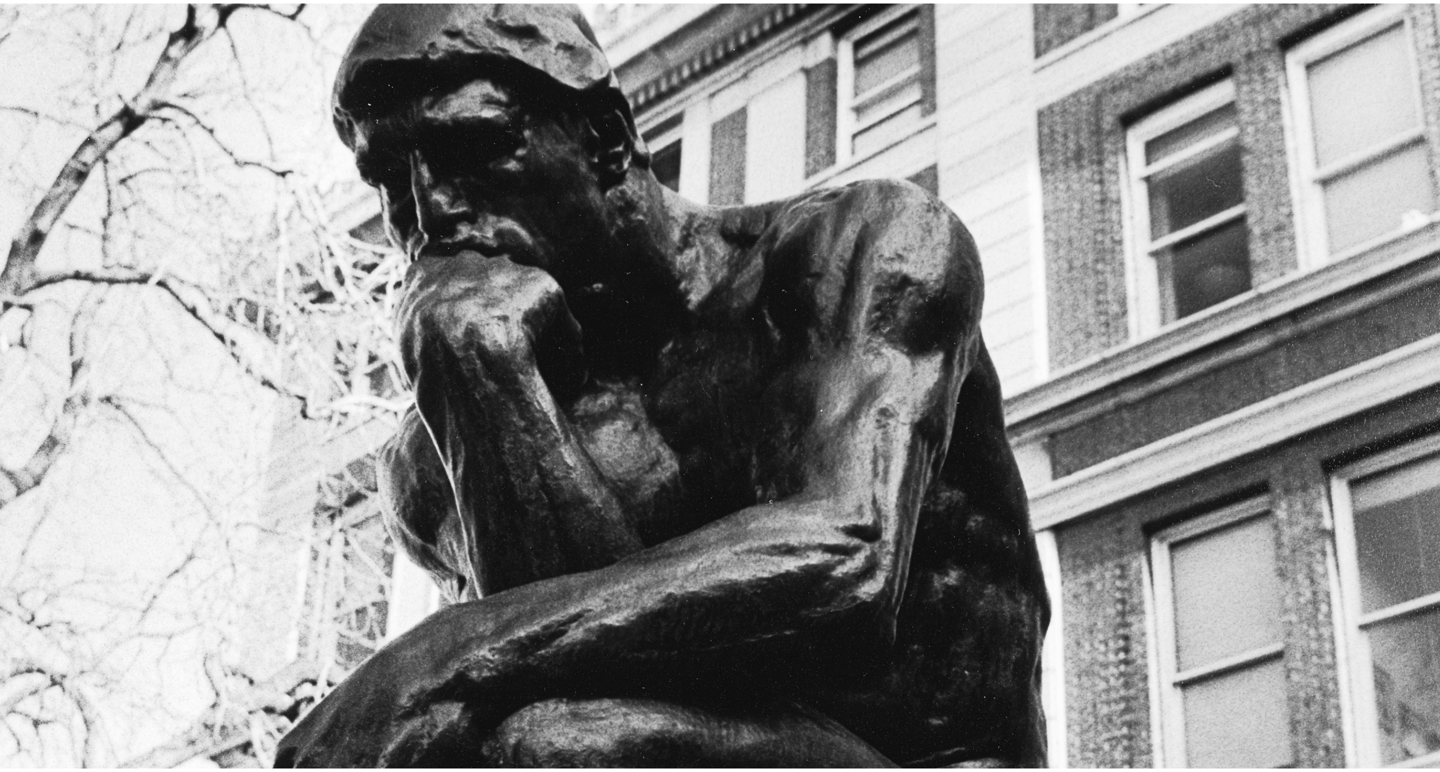
Graduate Career Placement Center
Phone: 646-832-5941
seas-gcp@columbia.edu
career.engineering.columbia.edu.

For questions about student loans, contact:

Office of Student Financial Planning
210 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



FACULTY AND ADMINISTRATION

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Dennis A. Mitchell, D.D.S., M.P.H..
Interim Provost of the University

Shih-Fu Chang, Ph.D.
Dean

Andrew Laine, D.Sc.
Secretary

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Anish Agarwal
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Alexander Gaeta
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Oleg Gang
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Megan Heenan
Lecturer in the Discipline of Biomedical Engineering

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Wang Fong-Jen Professor of Mechanical Engineering

Bianca Howard
Assistant Professor of Mechanical Engineering

Daniel J. Hsu
Associate Professor of Computer Science

Anran Hu
Assistant Professor of Industrial Engineering and Operations Research

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James S. Im
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Xiaofan Fred Jiang
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Cedric Josz
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Jingyue Ju
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Soulaymane Kachani
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Bernard J. Lechner Professor of Electrical Engineering

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Zoran Kostic
Professor of Professional Practice in Electrical Engineering

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Associate Professor of Civil Engineering and Engineering Mechanics

Harish Krishnaswamy
Professor of Electrical Engineering

Christian Kroer
Associate Professor of Industrial Engineering and Operations Research

Sanat K. Kumar
Michael Bykhovsky and Charo Gonzalez-Bykhovsky Professor of Chemical Engineering

Ioannis Kymissis
Kenneth Brayer Professor of Electrical Engineering

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Feniosky Peña-Mora
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Maurice Ewing and J. Lamar Worzel Professor of Geophysics in the Department of Applied Physics and Applied Mathematics and Professor of Earth and Environmental Sciences

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Sakul Ratanalert
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Baishakhi Ray
Associate Professor of Computer Science

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Professor of Industrial Engineering and Operations Research

Kui Ren
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Kenneth A. Ross
Professor of Computer Science

Timothy Roughgarden
Professor of Computer Science

Dan Rubenstein
Professor of Computer Science

Nuttida Rungratsameetaweemana
Assistant Professor of Biomedical Engineering

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Professor of Computer Science

Jay Sethuraman
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Brian Smith
Assistant Professor of Computer Science

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Arthur D. Storke Memorial Professor of Earth and Environmental Sciences (Arts and Sciences) and Professor of Applied Physics and Applied Mathematics

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Stanley-Thompson Professor of Chemical Metallurgy in the Department of Earth and Environmental Engineering and Professor of Chemical Engineering

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Assistant Professor of Chemical Engineering

David G. Vallancourt
Senior Lecturer in the Discipline

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Professor of Computer Science

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Vijay Vedula
Assistant Professor of Mechanical Engineering

Latha Venkataraman
Lawrence Gussman Professor of Applied Physics and Professor of Chemistry

Venkat Venkatasubramanian
Samuel Ruben–Peter G. Viele Professor of Engineering

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Senior Lecturer in the Discipline of Computer Science

Sanja Vickovic
Assistant Professor of Biomedical Engineering (in the Herbert and Florence Irving Institute for Cancer Dynamics)

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YM Associate Professor of Computer Science

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University Professor and Mikati Foundation Professor of Biomedical Engineering

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Wen I. Wang
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Xiaodong Wang
Professor of Electrical Engineering

Michael I. Weinstein
Professor of Applied Mathematics and of Mathematics

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Professor of Materials Science and Applied Physics, and Earth and Environmental Science

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Harry West
Professor of Professional Practice in Industrial Engineering and Operations Research

Chris H. Wiggins
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Eugene Wu
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Mischa Schwartz
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Director of Annual Giving

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Sean Wiggins
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Academic Departments and Programs

KEY TO COURSE LISTINGS

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

DESIGNATORS

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

Course Designator	Department Subject
AHCE	Art History and Civil Engineering
AHIS	Art History
AMCS	Applied Math and Computer Science
AMST	American Studies
ANTH	Anthropology
APAM	Applied Physics and Applied Math
APBM	Applied Physics and Biomedical Engineering
APCH	Applied Physics and Chemical Engineering
APMA	Applied Mathematics
APPH	Applied Physics
ARCH	Architecture
ASCE	Asian Civilization: East Asian
ASCM	Asian Civilization: Middle East
ASTR	Astronomy
BIOC	Biology and Chemistry
BIOL	Biology
BIST	Biostatistics
BMCH	Biomedical and Chemical Engineering
BMCS	Biomedical Engineering, Computer Science
BMEB	Biomedical Engineering, Electrical Engineering, and Biology
BMEE	Biomedical Engineering and Electrical Engineering
BMEN	Biomedical Engineering
BMME	Biomedical Engineering and Mechanical Engineering
BUSI	Business
CBMF	Computer Science, Biomedical Engineering and Medical Informatics
CEEM	Civil Engineering and Engineering Mechanics
CEOR	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
CHNS	Chinese
CIEE	Civil Engineering and Earth and Environmental Engineering
CIEN	Civil Engineering
CLPS	Comparative Literature and Society and Psychoanalytic Center
CMBS	Cellular, Molecular, and Biophysical Studies
COCI	Contemporary Civilization
COMS	Computer Science
COSA	Computer Science, Industrial Engineering and Operations Research, Statistics, and Applied Physics and Applied Mathematics
CSEE	Computer Science and Electrical Engineering
CSEN	Computer Science and English
CSER	Center for Study of Ethnicity and Race
CSOR	Computer Science and Operations Research
DNCE	Dance
DRAN	Decision, Risk, and Operations
DROM	Decision, Risk, and Operations Management
EACE	Earth and Environmental Engineering and Civil Engineering
EACH	Earth and Environmental Engineering and Chemical Engineering
EAEE	Earth and Environmental Engineering
EAIA	Earth and Environmental Engineering and International and Public Affairs
ECBM	Electrical Engineering, Computer Science and Biomedical Engineering
ECIA	Earth and Environmental and Civil Engineering and International and Public Affairs
ECIE	Economics and Industrial Engineering

ECON	Economics
EEBM	Electrical Engineering and Biomedical Engineering
EECS	Electrical Engineering and Computer Science
EEEL	Earth and Environmental Engineering and Electrical Engineering
EEHS	Electrical Engineering and History
EEME	Electrical Engineering and Mechanical Engineering
EEOR	Electrical Engineering and Operations Research
EESC	Earth and Environmental Sciences
EHSC	Environmental Health Sciences
ELEN	Electrical Engineering
ENGI	Engineering
ENGL	English
EMME	Engineering Mechanics and Mechanical Engineering
ENME	Engineering Mechanics
FILM	Film
FINC	Finance
FREN	French
GERM	German
GRAP	Graphics
HIST	History
HSAM	History and Applied Mathematics
HUMA	Humanities
HUNG	Hungarian
IEME	Industrial Engineering and Mechanical Engineering
IEOR	Industrial Engineering and Operations Research
INAF	International Affairs
INTA	Earth and Environmental Engineering, Civil Engineering, and International and Public Affairs
LING	Linguistics
MATH	Mathematics
MEBM	Mechanical Engineering and Biomedical Engineering
MECE	Mechanical Engineering
MECH	Mechanical Engineering and Chemical Engineering
MECS	Mechanical Engineering and Computer Science
MEEM	Mechanical Engineering and Engineering Mechanics
MEIE	Mechanical Engineering and Industrial Engineering
MSAE	Materials Science and Engineering
MSIE	Management Science and Industrial Engineering and Operations Research
MUSI	Music
ORCA	Operations Research, Computer Science and Applied Mathematics
ORCS	Operations Research and Computer Science
PHED	Physical Education
PHIL	Philosophy
PHYS	Physics
PLAN	Planning
PLCE	Architecture Planning and Civil Engineering
POLS	Political Science
PSLG	Physiology
PSYC	Psychology
RELI	Religion
SCNC	Science
SIEO	Statistics and Industrial Engineering and Operations Research
SOCI	Sociology
SPAN	Spanish
STAT	Statistics
STCS	Statistics and Computer Science
URBS	Urban Studies
VIAR	Visual Arts

HOW COURSES ARE NUMBERED

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

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

Arts and Sciences

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

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

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

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

DIRECTORY OF CLASSES

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

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

APPLIED PHYSICS AND APPLIED MATHEMATICS

200 S. W. Mudd, MC 4701
212-854-4457
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Materials Science and Engineering: matsci.apam.columbia.edu

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Irving P. Herman, Professor Emeritus
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Michal Lipson, Electrical Engineering
Michael E. Mauel
Gerald A. Navratil
Ismail C. Noyan
Lorenzo M. Polvani, Earth and Environmental Sciences
Kui Ren
Christopher H. Scholtz, Professor Emeritus, Earth and Environmental Sciences
Adam Sobel, Earth and Environmental Sciences
Marc W. Spiegelman, Earth and Environmental Sciences
Latha Venkataraman
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Michael I. Weinstein
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Cheng-Shie Wuu, Radiation Oncology

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Carlos Paz-Soldan
Michael K. Tippett
Chris H. Wiggins, Systems Biology
Yuan Yang
Nanfang Yu

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Elizabeth Paul
Shanyin Tong
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Drew Youngren

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C. Julian Chen
Stephen L. Ostrow
Boyu Peng
Marco Zaider
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Perry S. Gerard
Yuan He
Anastasia Romanou
Anna Rozenshtein

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ADJUNCT SENIOR RESEARCH SCIENTISTS
John Marshall
Patricia Mooney

RESEARCH SCIENTISTS
Jacek Chowdhary
Gregory Elsaesser
Igor Geogdzhayev
Christopher J. Hansen
Jeffrey Levesque
Nikolas C. Logan
Catherine Naud

ASSOCIATE RESEARCH SCIENTISTS
Mikhail Alexandrov
Alexander F. Battey
Robert Field
Jeremy Hanson
Paul Lerner
Nils Leuthold
A. Oak Nelson
Ian G. Stewart
Francesca Turco
Veronika Zamkovska

ADJUNCT ASSOCIATE RESEARCH SCIENTISTS
Gabriel Chiodo

POSTDOCTORAL RESEARCH SCIENTISTS
Kossi Pierre Amenoagbadji
Zhengqian Cheng
Sai Kanth Dacha
Bithi De
Vladimir A. Kobzar
Simon H. Lee
Kelsey Malloy
Zachary S. McGraw
James M. Scott
Yun Zhao

POSTDOCTORAL RESEARCH FELLOWS
Miriam Blau
Johan Wärnegård

SPECIAL LECTURERS
Monique C. Katz

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

Current Research Activities in Applied Physics and Applied Mathematics

Applied Physics.

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

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

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

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

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

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

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

Laboratory and Computational Facilities in Applied Physics and Applied Mathematics

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

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

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

Current Research Activities and Laboratory Facilities in Materials Science and Engineering

See pages 179–180.

UNDERGRADUATE PROGRAMS

The Department of Applied Physics and Applied Mathematics offers three undergraduate programs: applied physics, applied mathematics, and materials science. The materials science program is described on pages 180–183.

The applied physics and applied mathematics programs provide an excellent preparation for graduate study or for careers in which mathematical and technical sophistication are important. Using the large number of electives in these programs, students can tailor their

APPLIED PHYSICS PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS[1]	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester	
				and ODE (3)[2]
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	UN1403 (3) UN2601 (3.5) Lab UN3081 (2)	Lab UN1494 (3)
CHEMISTRY/ BIOLOGY (choose one course)	CHEM UN1403 (3), **or** higher **or** BIOL UN2001 (4) **or** BIOL UN2005 (4), or higher			
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
REQUIRED TECH ELECTIVES	(3) Student's choice			
COMPUTER SCIENCE	ENGI E1006 (3)[3] any semester			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] Students with advanced standing may start the calculus sequence at a higher level (see page 12 for placement), in which case students are suggested to add linear algebra in the first two years.

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

[3] With permission of faculty adviser, students demonstrating familiarity with computational mathematics using Python may waive course requirement and use 3 credits for another technical course.

programs to fit their personal and career interests. By focusing their technical electives, students can obtain a strong base of knowledge in a specialized area. In addition to formal minors, some areas of specialization that are available are described on pages 55–56. All technical electives are normally at the 3000 level or above.

UNDERGRADUATE PROGRAM IN APPLIED PHYSICS

The applied physics program stresses the basic physics that underlies most developments in engineering and the mathematical tools that are important to both physicists and engineers. Since the advances in most branches of technology lead to rapid changes in state-of-the-art techniques, the applied physics program provides the student with a broad base of fundamental science and mathematics while retaining the opportunity for specialization through technical electives.

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

Opportunities for undergraduate research exist in the many research programs in applied physics. These include fusion and space plasma physics, optical and laser physics, and condensed matter physics. Undergraduate students can receive course credit for research or an independent project with a faculty member. Opportunities also exist for undergraduate students in the applied physics program to participate in this

APPLIED PHYSICS: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		APPH E3200 (3) Mechanics MSAE E3111 (3) Thermodynamics APMA E3101 (3) Linear algebra APPH E4901 (1) Seminar	APPH E3100 (3) Intro. to quantum mechanics APPH E3300 (3) Applied electromagnetism APMA E3102 (3) Partial differential equations	APPH E4300 (3) Applied electrodynamics APPH E4100 (3) Quantum physics Course in first AP area (3) APPH E4903 (2) Seminar	Course in second AP area (3) APPH E4018 (2) Laboratory
ELECTIVES	**TECH**[1]	3 points	3 points	2 points	9 points
	NONTECH OR TECH	3 points	3 points	3 points	3 points
TOTAL POINTS		16	15	16	17

[1] They must include at least 2 points of laboratory courses. If PHYS UN3081 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.

research through part-time employment during the academic year and full-time employment during the summer, either at Columbia or as part of the NSF REU program nationwide. Practical research experience is a valuable supplement to the formal course of instruction. Applied physics students participate in an informal undergraduate seminar to study current and practical problems in applied physics and obtain hands-on experience in at least two advanced laboratory courses.

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

DYNAMICAL SYSTEMS:
APMA E4101 or PHYS GU4003

OPTICAL OR LASER PHYSICS:
APPH E4110 or E4112

NUCLEAR SCIENCE: APPH E4010

PLASMA PHYSICS: APPH E4301

PHYSICS OF FLUIDS: APPH E4200

SOLID-STATE/CONDENSED MATTER PHYSICS:
PHYS GU4018

BIOPHYSICAL MODELING: APMA E4400

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

All students must take 30 points of electives in the third and fourth years, of which 17 points must be technical courses approved by the adviser. The 17 points include 2 points of an advanced laboratory in addition to *APPH E4018*. Technical electives must be at the 3000 level or above unless prior approval is obtained from the department. A number of approved technical electives are listed in the section on specialty areas. The remaining points of electives are intended primarily as an opportunity to complete the absolutely mandatory four-year, 27-point nontechnical requirement for the B.S. degree, but if this 27-point nontechnical requirement has been met already, then any type of coursework can satisfy these elective points.

UNDERGRADUATE PROGRAM IN APPLIED MATHEMATICS

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

While it is common for students in the program to go on to graduate school, many graduating seniors will find employment directly in industry, government, education, or other fields.

Of the 27 points of elective content in the third and fourth years, at least 15 points of technical courses approved

APPLIED MATHEMATICS PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS[1]	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester	**and** ODE (3)[2]
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	UN1403 (3)[3] UN2601 (3.5) Lab UN3081 (2)[4]	Lab UN1494 (3)[4]
CHEMISTRY/ BIOLOGY (choose one course)	CHEM UN1403 (3), or higher **or** BIOL UN2001 (4) **or** BIOL UN2005 (4), or higher			
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
REQUIRED TECH ELECTIVES	(3) Student's choice			
COMPUTER SCIENCE	ENGI E1006 (3) any semester			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	E1102 (4) either semester			

[1] Students with advanced standing may start the calculus sequence at a higher level (see page 12 for placement), in which case students are suggested to add linear algebra in the first two years.

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

[3] Transfer students who have not fulfilled the physics requirement prior to enrolling at Columbia may substitute this course with PHYS BC3001.

[4] Or a lab course in Astronomy, Astrophysics, Biology, or Chemistry.

by the adviser must be taken. The remaining points of electives are intended primarily as an opportunity to complete the absolutely mandatory four-year, 27-point nontechnical requirement for the B.S. degree, but if this 27-point nontechnical requirement has been met already, then any type of coursework can satisfy these elective points.

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

UNDERGRADUATE DOUBLE MAJOR IN APPLIED PHYSICS AND APPLIED MATHEMATICS

Students satisfy all requirements for both majors, except for the seminar requirements. They are required to take both senior seminars, *APMA E4903* and *APPH E4903* (taking one in the junior year and one in the senior year, due to timing conflicts), but not the junior seminars, *APMA E4901* and *APPH E4901.* A single foundational course may be used to fulfill a requirement in both majors. Students must maintain a GPA at or above 3.75, and must graduate with at least 143 points, 15 above the regular 128-point requirement. These extra 15 points should be technical electives appropriate for one or both majors.

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

SPECIALTY AREAS IN APAM

Both applied physics and applied mathematics students can focus their technical electives and develop a strong base of knowledge in a specialty area. There is no requirement to focus electives, so students may take as many or as few of

APPLIED MATHEMATICS: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		APMA E3101 (3)[1] Linear algebra (Applied math, I) APMA E4204 (3)[1] Complex variables APMA E4300 (3) Introduction to numerical methods (Computational math, I) APMA E4901 (0) Seminar	APMA E3102 (3)[1] Partial differential equations (Applied math, II) APMA E4101 (3) Introduction to dynamical systems (Applied math, III) Course from Group A[2]	MATH GU4061 (3)[1] Modern analysis APMA E4903 (3 or 4) Seminar Course from Group B[2]	APMA E3900 (3)[3] Research Courses designated MATH, APMA, or STAT (3)
ELECTIVES	TECH[4]	3 points	3 points	3 points	6 points
	NONTECH	3 points	3 points	3 points	3 points
TOTAL POINTS		15	15	16	15

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

[2] One course from Group A (Probability) and one course from Group B (Applied Probability/Statistics) required for graduation. Group A: IEOR E3658: Probability for engineers or IEOR E4150: Introduction to probability and statistics; STAT GU4203: Probability theory; MATH W4155: Probability theory. Group B: IEOR E3106: Stochastic systems and applications; IEOR E4106: Stochastic models; STAT GU4204: Statistical inference; STAT GU4207: Elementary stochastic processes; COMS W4771: Machine learning.

[3] With an adviser's permission, an approved technical elective may be substituted.

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

the recommended courses in a specialty area as is appropriate to their schedules and interests. Some specialties are given below, but this is not an exclusive list, and others can be worked out in coordination with the student's adviser. The courses that are often taken, or in some cases need to be taken, in the junior year are denoted with a "J."

Technical Electives

- Applications of Physics

  Courses that will give a student a broad background in applications of physics:

ELEN E3000x: Circuits, systems, and electronics (J)
MSAE E3010x: Introduction to materials science, I
APPH E4010x: Intro to nuclear science
PHYS GU4018y: Solid state physics
APMA E4101x: Intro to dynamical systems
APPH E4110y: Modern optics
APPH E4112x: Laser physics
APPH E4200x: Physics of fluids
APPH E4301y: Intro to plasma physics

- Earth and Atmospheric Sciences

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

ATMOSPHERE, OCEANS, AND CLIMATE

APAM E3109: Climate physics
EESC GU4008: Intro to atmospheric science
APPH E4200: Physics of fluids
APPH E4210: Geophysical fluid dynamics
EESC GU4925: Principles of physical oceanography
EESC GU4930: Earth's oceans and atmosphere

SOLID EARTH GEOPHYSICS

EESC UN3201: Solid earth dynamics
EESC GU4085: Geodynamics
EESC GU4113: Intro to mineralogy
EESC GU4300: Earth's deep interior
EESC GU4701: Intro to igneous petrology
EESC GU4949: Introduction to seismology

(See also courses listed under Scientific Computation and Computer Science below.)

- Basic Physics and Astrophysics

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

PHYS UN3002y: From quarks to the cosmos: applications of modern physics
ASTR UN3601x: General relativity, black holes, and cosmology (J)
ASTR UN3602y: Physical cosmology (J)
ASTR GU4001y: Astrophysics, I
APMA E4101x: Intro to dynamical systems

- Business and Finance

  The knowledge of physics and mathematics that is gained in the applied physics and applied mathematics programs is a strong base for a career in business or finance.

ECONOMICS

ECON UN3211x,y: Intermed microeconomics (J)
ECON UN3213x,y: Intermed macroeconomics (J)

INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

IEOR E4003x: Industrial economics
IEOR E4201x: The eng of management, I
IEOR E4202y: The eng of management, II

FINANCE

MATH GU4071x: Mathematics of finance
IEOR E4106y: Intro to operations research: stochastic models (J)
STAT GU4001x,y: Probability and statistics (J)
ECON GU4280x,y: Corporate finance
IEOR E4700x: Intro to financial engineering

- Mathematics Applicable to Physics

  Applied physics students can specialize in the mathematics that is applicable to physics. This specialization is particularly useful for students interested in theoretical physics.

MATH UN3386x: Differential geometry
APMA E4101x: Intro to dynamical systems
APMA E4301y: Numerical methods for partial differential equations
APMA E4302x: Methods in computational science
PHYS GU4019y: Mathematical methods of physics

- Fundamental Mathematics in Applied Mathematics

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

MATH UN3386x: Differential geometry
APMA E4101x: Intro to dynamical systems
APMA E4150x: Applied functional analysis
MATH GU4032x: Fourier analysis
MATH GU4062y: Modern analysis, II
STAT GU4001x, y: Intro to probability and statistics (J)
PHYS GU4386x-GU4387y: Geometrical concepts in physics

- Quantitative Biology

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

RECOMMENDED:

BIOL UN2005x-UN2006y: Intro biology, I and II
APPH E3400y: Physics of the human body
APMA E4400y: Intro to biophysical modeling

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

BIOLOGICAL MATERIALS

BIOL GU4070x: The biology and physics of single molecules
CHEN E4650x: Biopolymers

BIOMECHANICS

BMEN E3320y: Fluid biomechanics (J)
BMEN E4300y: Solid biomechanics (J)

GENOMICS AND BIOINFORMATICS

BIOL UN3037y: Whole genome bioinformatics (J)
ECBM E3060x: Intro to genomic information science and technology (J)
CBMF W4761y: Computational genomics

NEUROBIOLOGY

BIOL UN3004x: Neurobiology, I (J)
BIOL UN3005y: Neurobiology, II (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 recommended courses in quantitative biology at the 3000 level or above.

- Scientific Computation and Computer Science

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

MATH UN3020x: Number theory and cryptography (J)
COMS W3137x,y: Data structures and algorithms (or COMS W3139y: Honors data structures and algorithms) (J)
COMS W3157x,y: Advanced programming (J)
COMS W3203x,y: Discrete mathematics: intro to combinatorics and graph theory (J)
COMS W4203y: Graph theory
APMA E4300x: Intro to numerical methods
APMA E4301y: Numerical methods for partial differential equations
APMA E4302x: Methods in computational science
COMS W4701x,y: Artificial intelligence
COMS W4771y: Machine learning

- Solid-State Physics

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

PHYS UN3083y: Electronics laboratory (J)
MSAE E3110x: Introduction to materials science, I
ELEN E3106x: Solid state devices and materials (J)
MSAE E4100x: Crystallography
PHYS GU4018y: Solid state physics
MSAE E4206x: Electronic and magnetic properties of solids

UNDERGRADUATE PROGRAM IN MATERIALS SCIENCE

See page 180.

GRADUATE PROGRAMS

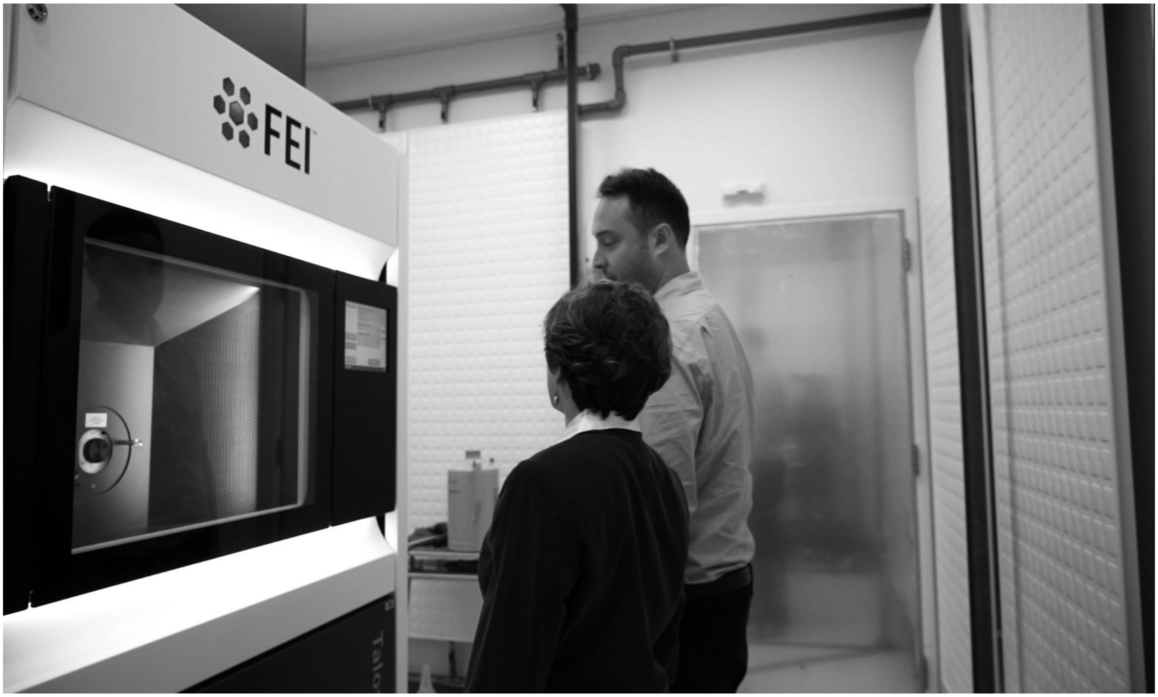
Financial aid is available for students pursuing a doctorate. Fellowships, scholarships, teaching assistantships, and graduate research assistantships are awarded on a competitive basis. The Aptitude Test of the Graduate Record Examination is optional for candidates for admission to the department and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

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

Ethics training is required of all students pursuing a doctorate.

M.S. Program in Applied Physics

This 30-point program of study leading to the degree of Master of Science, while emphasizing continued work in basic physics, permits many options in several applied physics specialties. The program may be considered simply as additional education in areas beyond the bachelor’s level, or as preparatory to



doctoral studies in the applied physics fields of plasma physics, laser and optical physics, or solid-state physics. Specific course requirements for the master's degree are determined in consultation with the faculty adviser, but students must complete at least four of the following courses or any other core course not listed below.

The core courses provide a student with a solid foundation in the fundamentals of applied physics. A core course is any 4000-level or above course with an APPH designator (excluding APPH E4901 and APPH E4903). The selection of core courses should be discussed with your faculty adviser.

APPH E4010: Introduction to nuclear science
APPH E4018: Applied physics laboratory
APPH E4100: Quantum physics of matter
APPH E4110: Modern optics
APPH E4112: Laser physics
APPH E4114: Quantum and nonlinear photonics
CHAP E4120: Statistical mechanics and computational methods
APPH E4130: Solar energy and storage
APPH E4200: Physics of fluids
APPH E4210: Geophysical fluid dynamics
APPH E4300: Applied electrodynamics
APPH E4990: Special topics in applied physics
APPH E6101: Plasma physics I
APPH E6102: Plasma physics II

In addition to core courses, students must also select elective courses to complete the degree requirements. Approved elective courses include any APPH course not used to satisfy the core course requirement, all 4000-level and above courses in the Applied Mathematics (excluding APMA E4901 and APMA E4903) and Materials Science and Engineering Programs, and 4000-level and above courses from the following departments: Computer Science, Data Science, Earth and Environmental Engineering, Electrical Engineering, Mechanical Engineering, Physics, and Mathematics (excluding seminar courses). Additional courses from other departments not listed above may also be applied toward the elective requirements, subject to the approval of the faculty adviser.

M.S. Program in Applied Mathematics

This 30-point program leads to a Master of Science degree. Students must complete five core courses and five electives. All degree requirements must be completed within five years. Students are required to maintain at least a 2.5 grade point average. If a student admitted to the Applied Mathematics M.S. only program is interested in the Ph.D. program, the student must reapply for admission. The core courses provide a student with a foundation in the fundamentals of applied mathematics and contribute 15 points of graduate credit toward the degree. A core course is any 4000-level or above course with an APMA designator (excluding APMA E4901 and APMA E4903). Students must complete five of the following courses or any other core course not listed below:

APMA E4007: Applied linear algebra
APMA E4008: Advanced linear algebra
APMA E4100: Applied analysis
APMA E4101: Intro to dynamical systems
APMA E4150: Applied functional analysis
APMA E4200: Partial differential equations
APMA E4204: Functions of a complex variable
APMA E4300: Intro to numerical methods
APMA E4301: Numerical methods for partial differential equations
APMA E4302: Intro to computational science
APMA E4306: Applied stochastic analysis
APMA E4990: Special topics in applied mathematics
APMA E6301: Analytic methods for partial differential equations
APMA E6302: Numerical analysis for partial differential equations
APMA E6901: Special topics in applied mathematics

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

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

Computer science elective courses include:

COMS W4232: Advanced algorithms
COMS W4236: Computational complexity
COMS W4241: Numerical algorithms and complexity
COMS W4252: Computational learning theory
COMS W4281: Quantum computing
COMS W4701: Artificial intelligence
COMS W4705: Natural language processing
COMS: W4771: Machine learning

Industrial engineering/operations research elective courses include**:

IEOR E4003: Industrial economics
IEOR E4004: Intro to operations research: deterministic models
IEOR E4007: Optimization: models and methods
IEOR E4106: Stochastic models
IEOR E4150: Introduction to probability and statistics
IEOR E4403: Advanced engineering and corporate economics
IEOR E4407: Game theoretic models of operations
IEOR E4700: Intro to financial engineering

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

Elective courses in Applied Physics, Physics, and Earth and Environmental Sciences include:

APPH E4100: Quantum mechanics
CHAP E4120: Statistical mechanics
APPH E4200: Physics of fluids
APPH E4210: Geophysical fluid dynamics
APPH E4300: Applied electrodynamics
APPH E6101: Plasma physics I
APPH E6102: Plasma physics II
PHYS GU4003: Advanced mechanics
PHYS GU4019: Mathematical methods in physics
EESC GU4008: Introduction to atmospheric science
EESC GU4040 Climate thermodynamics and energy transfer
EESC GU4925 Physical oceanography
EESC GR6928 Tropical meteorology

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

All 4000-level and above courses in the Department of Mathematics (excluding seminar courses):

BINF GU4001: Computer applications in health care & biomedicine
BMEN 4420: Signal modeling
ELEN 4815: Random signals and noise
EEME 4810: Digital signal processing
EEME 6601: Control theory
NBHV 4360: Theoretical neuroscience
STAT GU4001: Intro to probability and statistics
STAT GU4606: Elementary stochastic processes

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

M.S. Program in Materials Science and Engineering

See page 183.

M.S. Program in Medical Physics

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

Certification of Professional Achievement in Medical Physics

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

APPH E4330: Radiobiology
APPH E4500: Health physics
APPH E4600: Dosimetry
APBM E4650: Anatomy for physicists and engineers
APPH E6330: Diagnostic radiology physics
APPH E6335: Radiation therapy physics

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

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

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

Applied Mathematics

Applied mathematics deals with mathematical concepts and techniques used in various fields of science and engineering. Historically, mathematics was first applied with great success in astronomy and mechanics. Then it developed into a main tool for physics, other physical science, and engineering.

It is now becoming important in the biological, geological, economics, business, etc. With the coming of age of the computer, applied mathematics transcended its traditional style and now assumes an even greater importance and a new vitality.

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

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

The Atmospheric, Oceanic, and Earth Physics specialty includes research on dynamics of the atmosphere and the ocean; climate modeling; cloud physics; radiation transfer; remote sensing; geophysical/geological fluid dynamics; and geochemistry.

Courses:
APMA E4007: Applied linear algebra
APMA E4008: Advanced linear algebra
APMA E4100: Applied analysis
APMA E4101: Intro to dynamical systems
APMA E4150: Applied functional analysis
APMA E4200: Partial differential equations
APMA E4204: Functions of a complex variable
APMA E4300: Intro to numerical methods
APMA E4301: Numerical methods for partial differential equations
APMA E4302: Intro to computational science
APMA E4306: Applied stochastic analysis
APMA E6301: Analytic methods for partial differential equations
APMA E6302: Numerical analysis for partial differential equations

Related courses of specialization:
MATH GU4032: Fourier analysis
MATH GR6151: Analysis & Probability I
MATH GR6152: Analysis II
APMA E6901: Special topics in applied mathematics
COMS E4241: Numerical algorithms and complexity
EESC GU4008: Introduction to atmospheric science
APPH E4210: Geophysical fluid dynamics
APMA E9815: Geophysical fluid dynamics seminar
PHYS GU4019: Mathematical methods in physics
APMA E8308: Asymptotic methods in applied mathematics
APPH E4210: Geophysical fluid dynamics

Materials Science and Engineering Program

See page 184.

Applied Physics

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

Plasma Physics

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

Optical and Laser Physics

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

Solid-State Physics

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

COURSES IN APPLIED PHYSICS

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

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

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

APAM E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

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

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

APPH E4010x Introduction to nuclear science
3 pts. Lect: 3. Professor Ostrow.
Prerequisite(s): MATH UN1202 or APMA E2000, and UN2030 and PHYS UN1403 or equivalents. Introductory course for individuals with an interest in medical physics and other branches of radiation science. Topics include basic concepts, nuclear models, semiempirical mass formula, interaction of radiation with matter, nuclear detectors, nuclear structure and instability, radioactive decay process and radiation, particle accelerators, and fission and fusion processes and technologies.

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

APCH E4080x Soft condensed matter
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E3111, CHEE E3010, or equivalent. Course is aimed at senior undergraduate and graduate students. Introduces fundamental ideas, concepts, and approaches in soft condensed matter with emphasis on biomolecular systems. Covers the broad range of molecular, nanoscale, and colloidal phenomena with revealing their mechanisms and physical foundations. The relationship between molecular architecture and interactions and macroscopic behavior are discussed for the broad range of soft and biological matter systems, from surfactants and liquid crystals to polymers, nanoparticles, and biomolecules. Modern characterization methods for soft materials, including X-ray scattering, molecular force probing, and electron microcopy are reviewed. Example problems, drawn from the recent scientific literature, link the studied materials to the actively developed research areas. Course grade based on midterm and final exams, weekly homework assignments, and final individual/team project.

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

APPH E4110y Modern optics
3 pts. Lect: 3. Professor Yu.
Prerequisite(s): APPH E3300. Ray optics, matrix formulation, wave effects, interference, Gaussian beams, Fourier optics, diffraction, image formation, electromagnetic theory of light, polarization and crystal optics, coherence, guided wave and fiber optics, optical elements, photons, selected topics in nonlinear optics.

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

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

CHAP E4120y Statistical mechanics and computational methods
3 pts. Lect: 3. Professor O'Shaughnessy.
Prerequisite(s): Thermodynamics, statistics, or instructor's permission. Boltzmann's entropy hypothesis and its restatement to calculate the Helmholtz and Gibbs free energies and the grand potential. Applications to interfaces, liquid crystal displays, polymeric materials, crystalline solids, heat capacity and electrical conductivity of crystalline materials, fuel cell solid electrolytes, rubbers, surfactants, molecular self-assembly, ferroelectricity. Computational methods for molecular systems. Monte Carlo (MC) and molecular dynamics (MD) simulation methods. MC method applied to liquid-gas and ferromagnetic phase transitions. Deterministic MD simulations of isolated gases and liquids. Stochastic MD simulation methods.

APPH E4130x Solar energy and storage
3 pts. Lect: 3. Professor Chen.
Prerequisite(s): General physics (PHYS UN1401x, UN1402y, UN1403x, UN1601x, and UN1602y), freshman mathematics including ordinary differential equations (MATH UN1201 and UN1202, E1210). Familiarity in thermodynamics, electromagnetism, quantum mechanics, solid-state. Nature of solar radiation as electromagnetic waves and photons. Availability of solar radiation at different times and at various places in the world. Thermodynamics of solar energy. Elements of quantum mechanics for the understanding of solar cells, photosynthesis, and electrochemistry. Theory, design, manufacturing, and installation of solar cells. Lithium-ion rechargeable batteries and other energy-storage devices. Architecture of buildings to utilize solar energy.

APPH/CHEM E/GU 4164x Electric field effects in catalysis
1.5 pts. Lect: 2.5. Not offered in 2024–2025. Nuckolls, Rovis, Roy, and Venkatataman.
Prerequisite(s): physical chemistry or equivalent. Real-time exposition of an emerging area of study at the interface between chemistry, physics, engineering, and biology to understand and control how electric fields can be used to catalyze chemical transformations. Taught by a cross-disciplinary group of faculty. Topics covered: (1) theoretical underpinnings for catalysis in nanoscale electrical environments, (2) experimental tools used to study these chemical transformations, (3) experimental demonstrations of catalysis in electric fields. Each topic will draw on elements of organometallic/organic catalysis, quantum mechanics, enzymatic catalysis, and nano electronics to form the basis for understanding this new branch of catalytic science.

APPH E4200x Physics of fluids
3 pts. Lect: 3. Professor Polvani.
Prerequisite(s): APMA E3102 or equivalent; PHYS UN1401 or UN1601 or equivalent. An introduction to the physical behavior of fluids for science and engineering students. Derivation of basic equations of fluid dynamics: conservation of mass, momentum, and energy. Dimensional analysis. Vorticity. Laminar boundary layers. Potential

flow. Effects of compressibility, stratification, and rotation. Waves on a free surface; shallow water equations. Turbulence.

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

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

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

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

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

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

APBM E4650x Anatomy for physicists and engineers
3 pts. Lect: 3. Professors Ahmad, Rozenshtein, Gerard, and Katz.
Prerequisite(s): Engineering or physics background. Systemic approach to the study of the human body from a medical imaging point of view: skeletal, respiratory, cardiovascular, digestive, and urinary systems, breast and women's issues, head and neck, and central nervous system. Lectures are reinforced by examples from clinical two- and three-dimensional and functional imaging (CT, MRI, PET, SPECT, U/S, etc.).

APPH E4710x Radiation instrumentation and measurement laboratory, I
3 pts. Lect: 1. Lab: 4. Professors Ostrow and Zaider.
Prerequisite or corequisite: APPH E4010. Theory and use of alpha, beta, gamma, and X-ray detectors and associated electronics for counting, energy spectroscopy, and dosimetry; radiation safety; counting statistics and error propagation; mechanisms of radiation emission and interaction. (Topic coverage may be revised.)

APAM E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

APPH E4901x Seminar: problems in applied physics
1 pt. Lect: 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. Topics change yearly.

APPH E4903x Seminar: problems in applied physics
2 pts. Lect: 1. Tutorial: 1. Professor Mauel.
Required for, and can be taken only by, all applied physics majors in the senior year. Discussion of specific and self-contained problems in areas such as applied electrodynamics, physics of solids, and plasma physics. Formal presentation of a term paper required. Topics change yearly.

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

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

APPH E6081x Solid state physics, I
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APPH E3100 or the equivalent. Knowledge of statistical physics on the level of MSAE E3111 or PHYS GU4023 strongly recommended. Crystal structure, reciprocal lattices, classification of solids, lattice dynamics, anharmonic effects in crystals, classical electron models of metals, electron band structure, and low-dimensional electron structures.

APPH E6101x Plasma physics, I
3 pts. Lect: 3. Professor Navratil.
Prerequisite(s): APPH E4300. Debye screening. Motion of charged particles in space- and time-varying electromagnetic fields. Two-fluid description of plasmas. Linear electrostatic and electromagnetic waves in unmagnetized and magnetized plasmas. The magnetohydrodynamic (MHD) model, including MHD equilibrium, stability, and MHD waves in simple geometries.

APPH E6102y Plasma physics, II
3 pts. Lect: 3. Professor Paz-Soldan.
Prerequisite(s): APPH E6101. Magnetic coordinates. Equilibrium, stability, and transport of toroidal plasmas. Ballooning and tearing instabilities. Kinetic theory, including Vlasov equation, Fokker-Planck equation, Landau damping, kinetic transport theory. Drift instabilities.

APPH E6110x Laser interactions with matter
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APPH E4112 or equivalent, and quantum mechanics. Principles and applications of laser-matter coupling, nonlinear optics, three- and four-wave mixing, harmonic generation, laser processing of surfaces, laser probing of materials, spontaneous and stimulated light scattering, saturation spectroscopy, multiphoton excitation, laser isotope separation, transient optical effects.

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

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

APPH E6333x or y Radiation therapy physics practicum

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

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

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

APPH E6340x or y Diagnostic radiology practicum
3 pts. Lab: 6. Professor Peng.
Prerequisite(s): Grade of B+ or better in APPH E6330 and instructor's permission. Practical applications of diagnostic radiology for various measurements and equipment assessments. Instruction and supervised practice in radiation safety procedures, image quality assessments, regulatory compliance, radiation dose evaluations and calibration of equipment. Students participate in clinical QC of the following imaging equipment: radiologic units (mobile and fixed), fluoroscopy units (mobile and fixed), angiography units, mammography units, CT scanners, MRI units and ultrasound units. The objective is familiarization in routine operation of test instrumentation and QC measurements utilized in diagnostic medical physics. Students are required to submit QC forms with data on three different types of radiology imaging equipment.

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

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

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

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

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

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

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

COURSES IN APPLIED MATHEMATICS

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

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

APMA E2101x and y Introduction to applied mathematics
3 pts. Lect: 3. Professor He.
Prerequisite(s): Calculus III. A unified, single-semester introduction to differential equations and linear algebra with emphases on (1) elementary analytical and numerical technique and (2) discovering the analogs on the continuous and discrete sides of the mathematics of linear operators: superposition, diagonalization, fundamental solutions. Concepts are illustrated with applications using the language of engineering, the natural sciences, and the social sciences. Students execute scripts in Mathematica and MATLAB (or the like) to illustrate and visualize course concepts (programming not required).

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

APMA E3101x Linear algebra
3 pts. Lect: 3. Professor He.
Matrix algebra, elementary matrices, inverses, rank, determinants. Computational aspects of solving systems of linear equations: existence-uniqueness of solutions, Gaussian elimination, scaling, ill-conditioned systems, iterative techniques. Vector spaces, bases, dimension. Eigenvalue problems, diagonalization, inner products, unitary matrices.

APMA E3102y Partial differential equations
3 pts. Lect: 3. Professor Tippett.
Prerequisite(s): MATH UN2030 or equivalent. Introduction to partial differential equations; integral theorems of vector calculus. Partial differential equations of engineering in rectangular, cylindrical, and spherical coordinates. Separation of the variables. Characteristic-value problems. Bessel functions, Legendre polynomials, other orthogonal functions; their use in boundary value problems. Illustrative examples from the fields of

electromagnetic theory, vibrations, heat flow, and fluid mechanics.

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

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

APMA E4008y Advanced linear algebra
3 pts. Lect: 3. Professor He.
Prerequisite(s): APMA E3101 or E4007.
Advanced topics in linear algebra with applications to data analysis, algorithms, dynamics and differential equations, and more. (1) General vector spaces, linear transformations, spaces isomorphisms; (2) spectral theory - normal matrices and their spectral properties, Rayleigh quotient, Courant-Fischer Theorem, Jordan forms, eigenvalue perturbations; (3) least square problem and Gauss-Markov Theorem; (4) singular value decomposition, its approximation properties, matrix norms, PCA and CCA.

APMA E4100x Applied analysis
3 pts. Lect: 3. Professor Ren.
Prerequisite(s): Strong background in multivariate calculus is required. Knowledge in elementary analysis (such as the delta-epsilon definition of continuity, convergence of sequences of real numbers, topocontinuity of real-valued functions). Elementary introduction to fundamental concepts and techniques in classical analysis; applications of such techniques in different topics in applied mathematics. Brief review of essential concepts and techniques in elementary analysis; elementary properties of metric and normed spaces; completeness, compactness, and their consequences; continuous functions and their properties; Contracting Mapping Theorem and its applications; elementary properties of Hilbert and Banach spaces; bounded linear operators in Hilbert spaces; Fourier series and their applications.

APMA E4101y Introduction to dynamical systems
3 pts. Lect: 3. Professor Li.
Prerequisite(s): APMA E3101 or MATH UN2010 (Linear Algebra), and MATH UN2030 (ODE), or their equivalents, or instructor's permission.
An introduction to the analytic and geometric theory of dynamical systems; basic existence, uniqueness and parameter dependence of solutions to ordinary differential equations; constant coefficient and parametrically forced systems; Fundamental solutions; resonance; limit points, limit cycles and classification of flows in the plane (Poincare-Bendixson Theorem); conservative and dissipative systems; linear and nonlinear stability analysis of equilibria and periodic solutions; stable and unstable manifolds; bifurcations, e.g., Andronov-Hopf; sensitive dependence and chaotic dynamics; selected applications.

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

APMA E4200x and y Partial differential equations
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Course in ordinary differential equations. Techniques of solution of partial differential equations. Separation of the variables. Orthogonality and characteristic functions, nonhomogeneous boundary value problems. Solutions in orthogonal curvilinear coordinate systems. Applications of Fourier integrals, Fourier and Laplace transforms. Problems from the fields of vibrations, heat conduction, electricity, fluid dynamics, and wave propagation are considered.

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

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

APMA E4301y Numerical methods for partial differential equations
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): APMA E4300 and APMA E3102 or APMA E4200 or equivalents. Numerical solution of differential equations, in particular partial differential equations arising in various fields of application. Presentation emphasizes finite difference approaches to present theory on stability, accuracy, and convergence with minimal coverage of alternate approaches (left for other courses). Method coverage includes explicit and implicit time-stepping methods, direct and iterative solvers for boundary-value problems.

APMA E4302x Methods in computational science
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APMA E4300, application and knowledge in C, Fortran or similar compiled language. Introduction to the key concepts and issues in computational science aimed at getting students to a basic level of understanding where they can run simulations on machines aimed at a range of applications and sizes from a single workstation to modern super-computer hardware. Topics include but are not limited to basic knowledge of unix shells, version control systems, reproducibility, OpenMP, MPI, and many-core technologies. Applications will be used throughout to demonstrate the various use cases and pitfalls of using the latest computing hardware.

APMA E4306y Applied stochastic analysis
3 pts. Lect: 3. Professor Tong.
Prerequisite(s): Elementary probability theory (IEOR E3658 or above) and stochastic process (on the level of the first part of IEOR E4106 or STAT G4264) are required. Knowledge on analysis (MATH GU4601 or above) and differential equations (APMA E4200 or above) are required. Knowledge on numerical methods (APMA E4300 and above) and programming skills are required. Provides elementary introduction to fundamental ideas in stochastic analysis for applied mathematics. Core material includes: (1) review of probability theory (including limit theorems),

and introduction to discrete Markov chains and Monte Carlo methods; (2) elementary theory of stochastic process, Ito's stochastic calculus, and stochastic differential equations; (3) introductions to probabilistic representation of elliptic partial differential equations (the Fokker-Planck equation theory); (4) stochastic approximation algorithms; and (5) asymptotic analysis of SDEs.

APMA E4901x Seminar: problems in applied mathematics
0 pts. Lect: 1. Professor Wiggins.
Required for, and can be taken only by, all applied mathematics majors in the junior year. Introductory seminars on problems and techniques in applied mathematics. Typical topics are nonlinear dynamics, scientific computation, economics, operations research, etc.

APMA E4903x Seminar: problems in applied mathematics
3–4 pts. Lect: 1. Tutorial: 2. Professor Wiggins.
Required for all applied mathematics majors in the senior year. Term paper required. Examples of problem areas are nonlinear dynamics, asymptotics, approximation theory, numerical methods, etc. Approximately three problem areas are studied per term.

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

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

APMA E6301x Analytic methods for partial differential equations
3 pts. Lect: 2. Professor Weinstein.
Prerequisite(s): Advanced calculus, basic concepts in analysis, APMA E3101 or E4200 or their equivalents, or instructor's permission. Introduction to analytic theory of PDEs of fundamental and applied science; wave (hyperbolic), Laplace and Poisson equations (elliptic), heat (parabolic) and Schroedinger (dispersive) equations; fundamental solutions, Green's functions, weak/distribution solutions, maximum principle, energy estimates, variational methods, method of characteristics; elementary functional analysis and applications to PDEs; introduction to nonlinear PDEs, shocks; selected applications.

APMA E6302x Numerical analysis of partial differential equations
3 pts. Lect: 2. Professor Du.
Prerequisite(s): APMA E3102 or E4200. Numerical analysis of initial and boundary value problems for partial differential equations. Convergence and stability of the finite difference method, the spectral method, the finite element method and applications to elliptic, parabolic, and hyperbolic equations.

APMA E6901x and y–E6901y Special topics in applied mathematics
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Advanced calculus and junior year applied mathematics, or their equivalents. May be repeated for credit. Topics and instructors from the Applied Mathematics Program and the staff change from year to year. For students in engineering, physical sciences, biological sciences, and other fields. Examples of topics include uncertainty quantification.

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

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

APMA E9815x or y Geophysical fluid dynamics seminar
1–3 pts. May be repeated for up to 10 points of credit. Not offered in 2024–2025.
Prerequisite(s): Instructor's permission. Problems in the dynamics of geophysical fluid flows.

COURSES IN MATERIALS SCIENCE AND ENGINEERING

See page 185.

BIOMEDICAL ENGINEERING

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

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

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

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

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

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

Facilities

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

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

UNDERGRADUATE PROGRAM

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

The objectives of the undergraduate program in biomedical engineering are as follows:

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

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

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

7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

The undergraduate curriculum is designed to provide broad knowledge of the physical and engineering sciences and their application to the solution of biological and medical problems. Students are strongly encouraged to take courses in the order specified in the course tables; deviations must be discussed with a departmental adviser and approved by the department before registration. The first two years provide a strong grounding in the physical and chemical sciences, engineering fundamentals, mathematics, and modern biology. This background is used to provide a unique physical approach to the study of biological systems. The last two years of the undergraduate program provide substantial exposure to fundamentals in biomedical engineering with emphasis on the integration of principles of biomedical engineering, quantitative analysis of physiology, and experimental quantification and measurements of biomedical systems.

The common core biomedical engineering curriculum provides a broad yet solid foundation in biomedical engineering. The flexible choice of technical electives in the Department of Biomedical Engineering, other departments in the Engineering School, as well as in other departments in the arts and sciences allows students to broaden their biomedical engineering education to their individualized interests for a personalized curriculum. These qualities allow the faculty to prepare students for activity in all contemporary areas of biomedical engineering. Graduates of the program are equipped for employment in the large industrial sector devoted to health care, which includes pharmaceuticals, medical devices, artificial organs, prosthetics and sensory aids, diagnostics, medical instrumentation, and medical imaging. Graduates also accept employment in oversight organizations (FDA, NIH, OSHA, and others), medical centers, and research institutes. They are prepared for graduate study in biomedical engineering and several related areas of engineering and the health sciences. Students can meet entrance requirements for graduate training in the various allied health professions. No more than three additional courses are required to satisfy entrance requirements for most U.S. medical schools.

All biomedical engineering students are expected to register for nontechnical electives, both those specifically required by the School of Engineering and Applied Science and those needed to meet the 27-point total of nontechnical electives required for graduation.

First and Second Years

As outlined in this bulletin, in the first two years, all engineering students are expected to complete a sequence of courses in mathematics, physics, chemistry, computer science, engineering, modern biology, English composition, and physical education, as well as nontechnical electives including the humanities. For most of these sequences, the students may choose from two or more tracks. If there is a question regarding the acceptability of a course as a nontechnical elective, please consult the approved listing of courses beginning on page 9 or contact your advising dean for clarification.

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

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

Third and Fourth Years

The biomedical engineering programs at Columbia are based on engineering and biological fundamentals. This is emphasized in our core requirements, which cannot be waived nor substituted. All students must take the two-semester introduction to biomedical engineering courses, *BMEN E3010* and *E3020: Biomedical engineering I & II*, which provide a broad yet solid foundation in the biomedical engineering discipline. In parallel, all students take the two-semester *Quantitative physiology, I* and *II* sequence (*BMEN E4001-E4002*), which is taught by biomedical engineering faculty and emphasizes quantitative applications of engineering principles in understanding biological systems and phenomena from molecular to organ system levels. In the fields of biomedical engineering, experimental techniques and principles are fundamental skills that good biomedical engineers must master. Beginning in junior year, all students take the two-semester sequence *Biomedical engineering laboratory, I & II (BMEN E3810, E3820)*. In this two-semester series, students learn through hands-on experience the principles and methods of biomedical engineering experimentation, measurement techniques, quantitative theories of biomedical engineering, data analysis, and independent design of biomedical engineering experiments, in parallel to the *Biomedical engineering I & II* and *Quantitative physiology I & II* courses. In addition, all students must take *BMEN E4110: Biostatistics for engineers*. In the senior year, students are required to take a two-semester capstone design course, *Biomedical engineering design (BMEN E3910 and E3920)*, in which students work within a team to tackle an open-ended design project in biomedical engineering. The underlying philosophy of these core requirements is to provide our biomedical engineering students with a broad knowledge and understanding of topics in the field of biomedical engineering.

Parallel to these studies in core courses, students are required to take flexible technical elective courses, which are defined in the following section. The curriculum prepares students who wish to pursue careers in medicine by satisfying most requirements in the premedical programs with no more than three additional courses. Some of these additional courses may also be counted as nonengineering technical electives. Please see the course tables for schedules leading to a bachelor's degree in biomedical engineering.

It is strongly advised that students

BIOMEDICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester		
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	UN1403 (3) UN2601 (3.5)	
CHEMISTRY (three tracks, choose one)	UN1403 (4) UN1604 (4) UN2045 (4)	UN1404 (4) UN1500 (3) (**or** semester 1) UN1507 (3) UN2046 (4), UN1507 (3)		
UNIVERSITY WRITING	CC1010 (3) either semester			
COMPUTER SCIENCE	ENGI E1006 (3) (**or** semester II)			
PHYSICAL EDUCATION[1]	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING[1]	ENGI E1102 (4) either semester			
NONTECHNICAL REQUIREMENTS[1]	HUMA UN1121 (3) **or** UN1123 (3)		HUMA CC1001, COCI CC1101, **or** Global Core (3–4)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
TECHNICAL REQUIREMENTS			ELEN E1201 Intro. to EE (3.5) BIOL UN2005 Intro. to biology, I (4)	APMA E2101 (3) Intro. to applied math BIOL UN2006 (4) Intro to biology, II
TOTAL POINTS[2]	20	19	14.5	15

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

[2] Estimations

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

Technical Elective Requirements

Technical electives provide in-depth understanding of a student's 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. 2000-level organic chemistry and biochemistry courses may also count toward technical electives; please consult your adviser.

Students are required to take 21 points of technical electives. Of these, at least 15 points must be clearly engineering in nature (Engineering Content Technical Electives) as defined below. In addition, at least 6 points of the Engineering Content electives must be from courses in the Department of Biomedical Engineering.

1. Engineering Content Technical Electives provide sufficient engineering content to count toward the 48 units of engineering courses required for ABET accreditation and are defined as:
   a. All 3000-level or higher courses in the Department of Biomedical Engineering, except *BMEN E4010, E4103, E4104, E4105, E4106, E4107, E4108, and E6510; additionally, BMEN E4000 001 in fall 2019*. (Note that only 3 points of *BMEN E3998* may be counted toward technical elective degree requirements.)
   b. All 3000-level or higher courses in the Department of Mechanical Engineering, except *MECE*

BIOMEDICAL ENGINEERING: THIRD AND FOURTH YEARS

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

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

E4007: Creative engineering and entrepreneurship

c. All 3000-level or higher courses in the Department of Chemical Engineering, except *CHEN E4020: Safeguarding intellectual and business property*

d. All 3000-level or higher courses in the Department of Electrical Engineering, except *EEHS E3900: History of telecommunications: from the telegraph to the internet*

e. All 3000-level or higher courses in the Civil Engineering and Engineering Mechanics program, except *CIEN E4128, E4129, E4130, E4131, E4132, E4133, E4134, E4135, E4136, E4138, and E4140*

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

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

Once 48 points of engineering content are satisfied, students may choose their remaining technical electives as defined at the beginning of this section.

If a 3000-level or greater course is cross listed between two departments, eligibility as an engineering content technical elective is determined by either of the listed departments in its designation, independent of order. At least one of the programs that are listed must be ABET-accredited to be considered engineering content. For example, APBM E4560 Anatomy for physicists & engineers and BMCH E4810 Artificial organs are both engineering content technical electives. Finally, a cross-listed course that is greater than or equal to 3000 level and with BMEN in its call letters will qualify as a BME Engineering Technical Elective.

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

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

BIOFABRICATION & NANOTECHNOLOGY

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

BIOINFORMATICS & MACHINE LEARNING

BIOL UN3041: Cell biology (3)
COMS W3101: Programming languages (1)
COMS W3137: Data structures and algorithms (4)
BINF G4006: Translational bioinformatics (3)
BINF G4015: Computational systems biology: proteins, networks, function (3)
ECBM E4040: Neural networks and deep learning (3)
ECBM E4060: Introduction to genomic information science and technology (3)
STAT GU4241: Statistical machine learning (3)
COMS W4252: Introduction to computational learning theory (3)
BMEN E4420: Biomedical signal processing and signal modeling (3)
BMEN E4460: Deep learning in biomedical imaging (3)
BMEN E4470: Deep learning in biomedical signal processing (3)

COMS W4701: Artificial intelligence (3)
CBMF W4761: Computational genomics (3)
COMS W4771: Machine learning (3)
BMEN E4895: Analysis and quantification of medical images (3)

BIOMATERIALS

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

BIOMECHANICS

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

BIOSIGNALS & BIOMEDICAL IMAGING

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

CELL AND TISSUE ENGINEERING

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

DESIGN, INNOVATION, AND ENTREPRENEURSHIP

MECE E3408: Computer graphics and design (3)
ENGI W4100: Research to Revenue (3)
BIOT GU4160: Biotechnology Law (3)
BIOT GU4161: Ethics in Biopharmaceutical Patent and Regulatory Law (3)
BIOT GU4200: Biopharmaceutical Development & Regulation (3)
BIOT GU4201: Biotechnology Development and Regulatory Issues (3)
BMEE E4740: Bioinstrumentation (3)
CHEN E4920: Pharmaceutical industry for engineers (3)

GENOMICS AND SYSTEMS BIOLOGY

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

NEURAL ENGINEERING

ELEN E3810: Signals and systems (3.5)
BMEB W4020: Computational neuroscience: circuits in the brain (3)
BMEE E4030: Neural control engineering (3)
BMEN E4050: Electrophysiology of human memory and navigation (0)
BMEN E4310: Solid biomechanics (3)
BMEN E4420: Biosignal process and modeling (3)
BMEN E4430: Principles of MRI (3)
ELEN E4810: Digital signal processing (3)
BMEN E4894: Biomedical imaging (3)

PREMED AND PRE-HEALTH PROFESSIONAL

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

ROBOTICS AND CONTROL OF BIOLOGICAL SYSTEMS

MECE E3100: Introduction to mechanics of fluids (3)
ENME E3105: Mechanics (4)
MECE E3113: Mechanics of solids (3)
BMEE E4030: Neural control engineering (3)
BMEN E4050: Electrophysiology of human memory and navigation (3)
MEBM E4439: Modeling and identification of dynamic systems (3)
MECE E4602: Introduction to robotics (3)
BMEE E4740: Bioinstrumentation (3)

To meet entrance requirements of most U.S. medical schools, students will need to take BIOC GU4501 Biochemistry: Structure and metabolism (4), CHEM GU2543 Organic chemistry laboratory (3), PHYS UN1494: Introduction to experimental physics (3), and PSYC UN1001: The science of psychology (3) as well.

DUAL DEGREE PROGRAMS

Integrated B.S./M.S. Program in Biomedical Engineering

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

M.D./M.S. Program in Biomedical Engineering

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

GRADUATE PROGRAMS

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

Columbia 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. Doctoral students will be enrolled in ENGI E6001–6004 and should consult their program for specific PDL requirements.

CURRICULUM AND EXAM REQUIREMENTS

Master's Degree

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

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

BIOINFORMATICS AND MACHINE LEARNING

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

BIOMATERIALS AND TISSUE ENGINEERING

BMEN E4210: Driving forces of biological systems (3)
BMCH E4500: Biological transport and rate processes (3)
BMEN E4501: Biomaterials and scaffold design (3)
BMEN E4510: Tissue engineering (3)
BMEN E4530: Drug and gene delivery (3)
BMEN E4550: Micro- and nanostructures in cellular engineering (3)
BMEN E4580: Fundamentals of nanobioscience and nanobiotechnology (3)
BMEN E4590: BioMems: cellular and molecular applications (3)
BMEN E6001: Current topics in nanbiotechnology and synthetic biology (3)
BMEN E6500: Tissue and molecular engineering laboratory (4)
BMEN E6505: Advanced biomaterials for tissue engineering (3)
BMEN E9100: Master's research (3)

BIOMECHANICS

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

BIOMEDICAL IMAGING

BMEN E4410: Ultrasound in diagnostic imaging (3)
BMEN E4420: Biomedical signal processing and signal modeling (3)
BMEN E4430: Principles of magnetic resonance

imaging (3)
BMEE E4740: Bioinstrumentation (3)
ELEN E4810: Digital signal processing (3)
BMEN E4840: Functional imaging for the brain(3)
BMEN E4894: Biomedical imaging (3)
BMEN E4895: Analysis and quantification of medical images (3)
BMEN E4898: Biophotonics (3)
BMEN E6410 : Principles and practices of in vivo magnetic resonance spectroscopy (3)
BMEN E9100: Master's research (3)

NEURAL ENGINEERING

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

DESIGN, INNOVATION, AND ENTREPRENEURSHIP

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

ROBOTICS AND CONTROL OF BIOLOGICAL SYSTEMS

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

Doctoral Degree

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

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

Doctoral Qualifying Examination

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

Doctoral Committee and Thesis

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

COURSES IN BIOMEDICAL ENGINEERING

BMEN E1001x Engineering in medicine
3 pts. Lect: 3. Not offered in 2024–2025.
The present and historical role of engineering in medicine and health care delivery. Engineering approaches to understanding organismic and cellular function in living systems. Engineering in the diagnosis and treatment of disease. Medical imaging, medical devices: diagnostic and surgical instruments, drug delivery systems, prostheses, artificial organs. Medical informatics and organization of the health care system. Current trends in biomedical engineering research.

BMEN E3010x Biomedical engineering, I
3 pts. Lect: 3. Professor Wang.
Prerequisite(s): BIOL UN2005 and UN2006, or instructor's permission. Corequisite(s): BMEN E4001, BMEN E3810. Various concepts within the field of biomedical engineering, foundational knowledge of engineering methodology applied to biological and/or medical problems through modules in biomechanics, biomaterials, and cell and tissue engineering.

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

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

BMEN E3810x Biomedical engineering laboratory, I
3 pts. Lab: 4. Professor Kyle.
Fundamental considerations of wave mechanics; design philosophies; reliability and risk concepts; basics of fluid mechanics; design of structures subjected to blast; elements of seismic design; elements of fire design; flood considerations; advanced analysis in support of structural design.

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

BMEN E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

BMEN E3910x-E3920y Biomedical engineering design, I and II
4 pts. Lect: 1. Lab: 3. Professors Hillman and Sajda.
A two-semester design sequence to be taken in the senior year. Elements of the design process, with specific applications to biomedical engineering: concept formulation, systems synthesis, design analysis, optimization, biocompatibility, impact on patient health and comfort, health care costs, regulatory issues, and medical ethics. Selection and execution of a project involving the design of an actual engineering device or system. Introduction to entrepreneurship, biomedical start-ups, and venture capital. Semester I: statistical analysis of detection/classification systems (receiver operation characteristic analysis, logistic regression), development of design prototype, need, approach, benefits and competition analysis. Semester II: spiral develop process and testing, iteration and refinement of the initial design/prototype, and business plan development. A lab fee of $100 each is collected.

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

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

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

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

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

BMEN E4010y Ethics for biomedical engineers
2 pts. Lect: 2. Not offered in 2024–2025.
Prerequisite(s): senior status in biomedical engineering or the instructor's permission. Covers a wide range of ethical issues expected to confront graduates as they enter the biotechnology industry, research, or medical careers. Topics vary and incorporate guest speakers from Physicians and Surgeons, Columbia Law School, Columbia College, and local industry.

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

BMEE E4030x Neural control engineering
3 pts. Lect: 3. Professor Wang.
Prerequisite(s): ELEN E3801. Topics include basic cell biophysics, active conductance and the Hodgkin-Huxley model, simple neuron models, ion channel models and synaptic models, statistical models of spike generation, Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, sensorimotor integration and optimal state estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and somatosensory pathway, neural encoding model: spike triggered average (STA) and spike triggered covariance (STC) analysis, neuronal response to

electrical micro-stimulation, DBS for Parkinson's disease treatment, motor neural prostheses, and sensory neural prostheses.

ECBM E4040x or y Neural networks and deep learning
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): BMEB W4020 or BMEE E4030 or ECBM E4090 or EECS E4750 or COMS W4771 or an equivalent. Developing features and internal representations of the world, artificial neural networks, classifying handwritten digits with logistics regression, feedforward deep networks, back propagation in multilayer perceptrons, regularization of deep or distributed models, optimization for training deep models, convolutional neural networks, recurrent and recursive neural networks, deep learning in speech, and object recognition.

BMEN E4050x or y Electrophysiology of human memory and navigation
3 pts. Lect: 3. Professor Jacobs.
Prerequisite(s): Instructor's permission. Human memory, including working, episodic, and procedural memory. Electrophysiology of cognition, noninvasive and invasive recordings. Neural basis of spatial navigation, with links to spatial and episodic memory. Computational models of memory, brain stimulation, lesion studies.

ECBM E4060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Cheng.
Introduction to computational biology with emphasis on genomic data science tools and methodologies for analyzing data, such as genomic sequences, gene expression measurements and the presence of mutations. Applications of machine learning and exploratory data analysis for predicting drug response and disease progression. Latest technologies related to genomic information, such as single-cell sequencing and CRISPR, and the contributions of genomic data science to the drug development process.

ECBM E4070y Computing with brain circuits of model organisms
3 pts. Lect: 3. Professor Lazar.
Prerequisite(s): ELEN E3801 or BIOL W3004, and Python programming experience, or instrtor's permission. Building the functional map of the fruit fly brain. Molecular transduction and spatio-temporal encoding in the early visual system. Predictive coding in the Drosophila retina. Canonical circuits in motion detection. Canonical navigation circuits in the central complex. Molecular transduction and combinatorial encoding in the early olfactory system. Predictive coding in the antennal lobe. The functional role of the mushroom body and the lateral horn. Canonical circuits for associative learning and innate memory. Projects in Python.

ECBM E4090x or y Brain computer interfaces (BCI) laboratory
3 pts. Lect: 2. Lab: 3. Professor Mesgarani.
Prerequisite(s): ELEN E3801. Hands-on experience with basic neural interface technologies. Recording EEG (electroencephalogram) signals using data acquisition systems (noninvasive scalp recordings). Real-time analysis and monitoring of brain responses. Analysis of intention and perception of external visual and audio signals.

BMEN E4100 BMakE—Biomedical device design & fabrication
3 pts. Lect: 3. Professor Kyle.
Recommended: Coursework in statics and/or dynamics, basic electrical principles, and basic computer programming. Hands-on course. Covers medical device design to develop basic fabrication skills. Includes central project theme, i.e., through individual modules, students create different components of a biomedical device. First offering focuses on creation of a device pertinent for COVID-19: a mechanical ventilator. The mechanical ventilator combines physics (fluid dynamics, pressure-flow relationships) with fabrication, (bio)materials, sensing, signal acquisition and processing, and controls. As a highly advanced, life-supporting device, its functional aspects can be decomposed into modules of this course to create a benchtop ventilator.

BMEN E4103x Anatomy of the thorax and abdomen
2 pts. Lect: 2. Not offered in 2024–2025.
Prerequisite(s): Graduate standing in Biomedical Engineering. Designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to their doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4104).

BMEN E4104x Anatomy laboratory: thorax and abdomen
2 pts. Lect: 2. Not offered in 2024–2025.
Prerequisite(s): Graduate standing in Biomedical Engineering. Corequisite(s): BMEN E4103.

BMEN E4105x Anatomy of the extremities
2 pts. Lect: 2. Not offered in 2024–2025.
Prerequisite(s): Graduate standing in Biomedical Engineering. Designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to their doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4106).

BMEN E4106x Anatomy laboratory: extremities
2 pts. Lab: 2. Not offered in 2024–2025.
Prerequisite(s): Graduate standing in Biomedical Engineering. Corequisite(s): BMEN E4105.

BMEN E4107x Anatomy of the head and neck
2 pts. Lect: 2. Not offered in 2024–2025.
Prerequisite(s): Graduate standing in Biomedical Engineering. Designed for the Biomedical Engineering graduate student interested in acquiring in-depth knowledge of anatomy relevant to their doctoral research. Lectures and tutorial sessions may be taken with or without the associated laboratory (BMEN E4108).

BMEN E4108x Anatomy laboratory: head and neck
2 pts. Lab: 2. Not offered in 2024–2025.
Prerequisite(s): Graduate standing in Biomedical Engineering. Corequisite(s): BMEN E4107.

BMEN E4110x Biostatistics for engineers
4 pts. Lect: 4. Professor Jacobs.
Prerequisite(s): MATH UN1202 or APMA E2000 and APMA E2101. Fundamental concepts of probability and statistics applied to biology and medicine. Probability distributions, hypothesis testing and inference, summarizing data and testing for trends. Signal detection theory and the receiver operator characteristic. Lectures accompanied by data analysis assignments using MATLAB and R as well as discussion of bioethics and case studies in biomedicine.

BMEN E4150x The cell as a machine
3 pts. Lect: 3.
Prerequisite(s): MATH UN1101 or equivalent. Corequisite(s): One semester of BIOL UN2005 or BIOC UN3501, and one semester of PHYS UN1401 or equivalent. Cells as complex micron-sized machines, basic physical aspects of cell components (diffusion, mechanics, electrostatics, hydrophobicity), energy transduction (motors, transporters, chaperones, synthesis complexes), basic cell functions. Biophysical principles, feedback controls for robust cell function, adaptation to environmental perturbations.

BMEN E4210y Driving forces of biological systems
4 pts. Lect: 4. Professor Sia.
Prerequisite(s): CHEM UN1404 and MATH UN1202 or AMPA E2000. Corequisite(s): BIOL UN2005 or equivalent. Introduction to the statistical mechanics and thermodynamics of biological systems, with a focus on connecting microscopic molecular properties to macroscopic states. Both classical and statistical thermodynamics will be applied to biological systems; phase equilibria, chemical reactions, and colligative properties. Topics in modern biology, macromolecular behavior in solutions and interfaces, protein-ligand binding, and the hydrophobic effect.

BMEN E4301x Structure, mechanics, and adaptation of bone
3 pts. Lect: 3. Not offered in 2024–2025.
Introduction to structure, physiology, and biomechanics of bone. Structure, function, and physiology of skeletal bones; linear elastic properties of cortical and trabecular bone; anisotropy and constitutive models of bone tissue; failure and damage mechanics of bone; bone adaptation and fracture healing; experimental determination of bone properties; and morphological analysis of bone microstructure.

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

BMEN E4305y Cardiac mechanics
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): BMEN E4310 and BMEN E4320 or

equivalents. Cardiac anatomy, passive myocardial constitutive properties, electrical activation, ventricular pump function, ventricular-vascular coupling, invasive and noninvasive measures of regional and global function, models for predicting ventricular wall stress. Alterations in muscle properties and ventricular function resulting from myocardial infarction, heart failure, and left ventricular assist.

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

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

BMEN E4330x Cellular bioengineering & therapeutics
3 pts. Lect: 3. Professor Cheng.
Prerequisite(s): General understanding of chemistry and biology. Explores cutting-edge field of cellular bioengineering and applications of cell therapies. Comprehensive understanding of the principles, techniques, and ethical considerations involved in cells for medical applications studied.

BMEN E4340x Biomechanics of cells
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): BMEN E3320 and BMEN E4300 or equivalents. Survey of experiments and theoretical analyses of the mechanical behavior of individual living nonmuscle cells. Emphasis on quantitative analytic description using continuum mechanics and molecular level theory from the standpoint of statistical mechanics and mechanical models. Mechanics of erythrocytes, leukocytes, endothelial cells, and fibroblasts; models of aggregation, adhesion, locomotion, amoeba motility, cell division and morphogenesis; molecular level models of actin, myosin, microtubules, and intermediate filaments and relation to mechanical properties of cells and cytoskeleton. Alternative models of cytoskeletal mechanics, foam theory, tensegrity. Analysis of experimental techniques including micropipette studies, optical and magnetic cytometry, and nanoindentation.

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

BMEN E4400x Wavelet applications in biomedical image and signal processing
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APMA E2101 or E3101 or equivalent. An introduction to methods of wavelet analysis and processing techniques for the quantification of biomedical images and signals. Topics include frames and overcomplete representations, multiresolution algorithms for denoising and image restoration, multiscale texture segmentation and classification methods for computer aided diagnosis.

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

BMEN E4420y Biomedical signal processing and signal modeling
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ELEN E3801 and either APMA E2101 or E3101 or instructor’s permission. Fundamental concepts of signal processing in linear systems and stochastic processes. Estimation, detection, and filtering methods applied to biomedical signals. Harmonic analysis, autoregressive model, Wiener and Matched filters, linear discriminants, and independent components. Methods are developed to answer concrete questions on specific data sets in modalities such as ECG, EEG, MEG, ultrasound. Lectures accompanied by data analysis assignments using MATLAB.

BMEN E4430x Principles of magnetic resonance imaging
3 pts. Lect: 3. Professor Vaughan.
Prerequisite(s): PHYS UN1403 and APMA E2101, or instructor’s permission. Fundamental principles of Magnetic Resonance Imaging (MRI), including the underlying spin physics and mathematics of image formation with an emphasis on the application of MRI to neuroimaging, both anatomical and functional. The course examines both theory and experimental design techniques.

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

BMEN E4450y Dental and craniofacial tissue engineering
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E3103, BMEN E4210, E4501, or equivalent. Principles of dental and craniofacial bioengineering, periodontal tissue engineering: beyond guided tissue regeneration, craniofacial regeneration by stem cells and engineered scaffolds, biomaterials: Engineering approaches in tissue regeneration, bone biology and development: instructive cues for tissue engineers.

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

BMEN E4470x Deep learning for biomedical signal processing
3 pts. Lect: 3. Professor Sajda.
Prerequisite(s): MATH UN1202 or APMA E2000 and APMA E2101. Recommended: background in Python programming. Introduction to methods in deep learning, focus on applications to biomedical signals and sequences. Review of traditional methods for analysis of signals and sequences. Temporal convolutional neural networks and recurrent neural networks. Long-short term memory (LSTM) models and deep state-space models. Theory and methods lectures accompanied with examples from biomedical signal and sequence

analysis, including analysis of electroencephalogram (EEG), electrocardiogram (ECG/EKG), and genomics. Programming assignments use tensorflow/keras. Exams and final project required.

BMCS E4480y Statistical machine learning for genomics
3 pts. Lect: 3. Professor Azizi.
Prerequisite(s): Proficiency in Python/R programming, and background in probability/statistics. Recommended: COMS W4771. Introduction to statistical machine learning methods using applications in genomic data and in particular high-dimensional single-cell data. Concepts of molecular biology relevant to genomic technologies, challenges of high dimensional genomic data analysis, bioinformatics preprocessing pipelines, dimensionality reduction, unsupervised learning, clustering, probabilistic modeling, hidden Markov models, Gibbs sampling, deep neural networks, gene regulation. Programming assignments and final project will be required.

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

BMCH E4500x or y Biological transport and rate processes
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEM UN2443, APMA E2101. Corequisite(s): BIOL UN2005. Convective and diffusive movement and reaction of molecules in biological systems. Kinetics of homogeneous and heterogeneous reactions in biological environments. Mechanisms and models of transport across membranes. Convective diffusion with and without chemical reaction. Diffusion in restricted spaces. Irreversible thermodynamic approaches to transport and reaction in biological systems.

BMEN E4500x Functional genomics: methods and applications
3 pts. Lect: 3. Professor McFaline-Figuero.
Prerequisite(s): BIOL UN2005, BIOL UN2006. Introduces approaches for the functional genomic analysis of biological systems and their use to define genotype-phenotype relationships. Genetic variation, gene expression and regulation at the epigenome, chromatin organization level, and link between gene and protein expression covered. Case studies covered: study of cancer and cancer-associated processes, neuro-biology, and organismal development. The presented methods study these events at the genome, epigenome, transcriptome, and proteome levels. Approaches that increase the resolution of functional genomic assays to the level of individual cells, spatial profiling, integration with genetic and chemical screening methods, and their application to chemical genomic approaches also studied. Programming assignments and a final project required.

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

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

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

BMEN E4525y Advanced cell and tissue engineering: from concepts to translation
3 pts. Lect: 3. Professor Arinzeh.
Prerequisite(s): Biology and Physiology. Covers advancements in the fields of cellular and developmental biology, molecular biology and materials science towards the development of “tissue engineered” therapies. Emphasis on tissue engineering therapies applied to musculoskeletal tissues, such as bone, cartilage, and skeletal muscle, and nervous tissues (central and peripheral nervous system). Design considerations and concepts in market analysis examined.

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

BMEN E4535y Immunoengineering with biomaterials and nanotechnology
3 pts. Lect: 3. Professor Correa.
Introduction to fundamental aspects of immunology and engineering strategies to modulate the immune system to improve human health. We will cover the innate and adaptive immune system and current methods to characterize the immune response. Applications focus on cancer, vaccines, and autoimmune disorders.

BMEN E4540y Bioelectrochemistry
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEM UN3079 and UN2443 or equivalent. Application of electrochemical kinetics to interfacial processes occurring in biomedical systems. Basics of electrochemistry, electrochemical instrumentation, and relevant cell and electrophysiology reviewed. Applications to interpretation of excitable and nonexcitable membrane phenomena, with emphasis on heterogeneous mechanistic steps. Examples of therapeutic devices created as a result of bioelectrochemical studies.

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

BMEN E4560y Dynamics of biological membranes
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): BIOL UN2005, BMEN E4001, or equivalent. The structure and dynamics of biological (cellular) membranes are discussed, with an emphasis on biophysical properties. Topics include membrane composition, fluidity, lipid asymmetry, lipid-protein interactions, membrane turnover, membrane fusion, transport, lipid phase behavior. In the second half of the semester, students will lead discussions of recent journal articles.

BMEN E4570x Science and engineering of body fluids
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): General chemistry, organic chemistry, and basic calculus. Body fluids as a dilute solution of polyelectrolyte molecules in water. Study of physical behavior as affected by the presence of ions in surrounding environments. The physics of covalent, ionic, and hydrogen bonds are reviewed, in relation to the structure/properties of the body fluid. Selected physiological processes are examined in physical-chemical terms for polymers.

BMEN E4580y Foundations of nanobioscience and nanobiotechnology
3 pts. Lect: 3. Professor Hess.
Prerequisite(s): BIOL UN2005, UN2006, BMEN E4001-E4002 or instructor's permission.

Fundamentals of nanobioscience and nanobiotechnology, scientific foundations, engineering principles, current and envisioned applications. Includes discussion of intermolecular forces and bonding, of kinetics and thermodynamics of self-assembly, of nanoscale transport processes arising from actions of biomolecular motors, computation and control in biomolecular systems, and of mitochondrium as an example of nanoscale factory.

BMEN E4590x BioMems: cellular and molecular applications
3 pts. Lect: 3. Professor Sia.
Prerequisite(s): Chemistry, CHEM UN2443, or CHEM UN3545 or equivalent, MATH UN1201 or APMA E2000, BIOL UN2005, and UN2006. Topics include biomicroelectromechanical, microfluidic, and lab-on-a-chip systems in biomedical engineering, with a focus on cellular and molecular applications. Microfabrication techniques, biocompatibility, miniaturization of analytical and diagnostic devices, high-throughput cellular studies, microfabrication for tissue engineering, and in vivo devices.

BMEN E4601y Cellular electricity
3 pts. Lect: 2. Lab: 1. Not offered in 2024–2025.
Bioelectricity of the cell membrane. Basis of cell resting voltage, voltage changes that lead to the action potential and electrical oscillations used in sensing systems. Laboratory includes building electronic circuits to measure capacitance of artificial membranes and ion pumping in frog skin. Lab required.

APBM E4650x Anatomy for physicists and engineers
3 pts. Lect: 3. Professors Katz and Rozenshtein.
Prerequisite(s): Engineering or physics background. A systemic approach to the study of the human body from a medical imaging point of view: skeletal, respiratory, cardiovascular, digestive, and urinary systems, breast and women's issues, head and neck, and central nervous system. Lectures are reinforced by examples from clinical two- and three-dimensional and functional imaging (CT, MRI, PET, SPECT, U/S, etc.).

BMME E4702x Advanced musculoskeletal biomechanics
3 pts. Lect: 2.5. Lab: 0.5. Not offered in 2024–2025.
Advanced analysis and modeling of the musculoskeletal system. Topics include advanced concepts of 3D segmental kinematics, musculoskeletal dynamics, experimental measurements of joint kinematics and anatomy, modeling of muscles and locomotion, multibody joint modeling, introduction to musculoskeletal surgical simulations.

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

MEBM E4710x or y Morphogenesis: shape and structure in biological materials
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Courses in mechanics, thermodynamics, and ordinary differential equations at the undergraduate level or instructor's permission. Introduction to how shape and structure are generated in biological materials using engineering approach emphasizing application of fundamental physical concepts to a diverse set of problems. Mechanisms of pattern formation, self-assembly, and self-organization in biological materials, including intracellular structures, cells, tissues, and developing embryos. Structure, mechanical properties, and dynamic behavior of these materials. Discussion of experimental approaches and modeling. Course uses textbook materials as well as collection of research papers.

BMEN E4738y Transduction and acquisition of biomedical data
3 pts. Lect: 2. Lab: 1. Not offered in 2024–2025.
Data transduction and acquisition systems used in biomedicine. Assembly of biotransducers and the analog/digital circuitry for acquiring electrocardiogram, electromyogram, and blood pressure signals. Each small group will develop and construct a working data acquisition board, which will be interfaced with a signal generator to elucidate the dynamics of timing constraints during retrieval of biodata. Lab required.

BMEE E4740y Bioinstrumentation
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ELEN E1201, COMS W1005. Hands-on experience designing, building, and testing the various components of a benchtop cardiac pacemaker. Design instrumentation to measure biomedical signals as well as to actuate living tissues. Transducers, signal conditioning electronics, data acquisition boards, the Arduino microprocessor, and data acquisition and processing using MATLAB will be covered. Various devices will be discussed throughout the course, with laboratory work focusing on building an emulated version of a cardiac pacemaker.

BMEN E4750y Sound and hearing
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): PHYS UN1401 and MATH UN1105-MATH UN1106. Introductory acoustics, basics of waves and discrete mechanical systems. The mechanics of hearing—how sound is transmitted through the external and middle ear to the inner ear, and the mechanical processing of sound within the inner ear.

CBMF W4761y Computational genomics
3 pts. Lect: 3. Professor Pe'er.
Prerequisite(s): Working knowledge of at least one programming language, and some background in probability and statistics. Computational techniques for analyzing and understanding genomic data, including DNA, RNA, protein and gene expression data. Basic concepts in molecular biology relevant to these analyses. Emphasis on techniques from artificial intelligence and machine learning. String-matching algorithms, dynamic programming, hidden Markov models, expectation-maximization, neural networks, clustering algorithms, support vector machines. Students with life sciences backgrounds who satisfy the prerequisites are encouraged to enroll.

BMCH E4810y Artificial organs
3 pts. Lect: 3. Not offered in 2024–2025.
Analysis and design of replacements for the heart, kidneys, and lungs. Specification and realization of structures for artificial organ systems.

BMEN E4840y Functional imaging for the brain
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APMA E2101, APMA E4200, ELEN E3801, or instructor's permission. Fundamentals of modern medical functional imaging. In-depth exploration of functional magnetic resonance imaging (fMRI), arterial spin labeling (ASL), and positron emission tomography (PET). Human brain anatomy, physiology, and neurophysiological bases underlying each functional imaging. Statistical and digital signal processing methods specific for functional image analysis. Final cumulative project requiring coding in MATLAB, Python, R, or C.

BMEN E4894x Biomedical imaging
3 pts. Lect: 3. Not offered in 2024–2025.
Covers image formation, methods of analysis, and representation of digital images. Measures of qualitative performance in the context of clinical imaging. Algorithms fundamental to the construction of medical images via methods of computed tomography, magnetic resonance, and ultrasound. Algorithms and methods for the enhancement and quantification of specific features of clinical importance in each of these modalities.

BMEN E4898y Biophotonics
3 pts. Lect: 3.
Prerequisite(s): BMEN E4894 Biomedical imaging, PHYS UN1403 Classical and quantum waves, or instructor's permission. Provides a broad-based introduction into the field of Biophotonics. Fundamental concepts of optical, thermal, and chemical aspects of the light-tissue interactions will be presented. The application of these concepts for medical therapy and diagnostics will be discussed. The course includes theoretical modeling of light-tissue interactions as well as optical medical instrument design and methods of clinical data interpretation.

BMEN E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

BMEN E4999x and y Graduate fieldwork
1–2 pts. Professor Hung.
Prerequisite(s): Obtained internship and approval from faculty adviser. BMEN graduate

students only. Only for BMEN graduate students who need relevant work experience as part of their program of study. Final reports required. May not be taken for pass/fail credit or audits.

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

BMEN E6001x Current topics in nanobiotechnology and synthetic biology
3 pts. Lect: 3. Professor Hess.
Targeted toward graduate students; undergraduate students may participate with permission of the instructor. Review and critical discussion of recent literature in nanobiotechnology and synthetic biology. Experimental and theoretical techniques, critical advances. Quality judgments of scientific impact and technical accuracy. Styles of written and graphical communication, the peer review process.

BMEN E6003y Computational modeling of physiological systems
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): BMEN E4001 and E4002 or equivalent, and APMA E4200 or equivalent. Advanced computational modeling and quantitative analysis of selected physiological systems from molecules to organs. Selected systems are analyzed in depth with an emphasis on modeling methods and quantitative analysis. Topics may include cell signaling, molecular transport, excitable membranes, respiratory physiology, nerve transmission, circulatory control, auditory signal processing, muscle physiology, data collection and analysis.

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

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

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

EEBM E6020y Methods of computational neuroscience
4.5 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): BMEB W4020. Formal methods in computational neuroscience including methods of signal processing, communications theory, information theory, systems and control, system identification and machine learning. Molecular models of transduction pathways. Robust adaptation and integral feedback. Stimulus representation and groups. Stochastic and dynamical systems models of spike generation. Neural diversity and ensemble encoding. Time encoding machines and neural codes. Stimulus recovery with time decoding machines. MIMO models of neural computation. Synaptic plasticity and learning algorithms. Major project(s) in MATLAB.

BMEE E6030x Neural modeling and neuroengineering
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ELEN E3801, and either APMA E2101 or E3101, or equivalent, or instructor's permission. Engineering perspective on the study of multiple levels of brain organization, from single neurons to cortical modules and systems. Mathematical models of spiking neurons, neural dynamics, neural coding, and biologically-based computational learning. Architectures and learning principles underlying both artificial and biological neural networks. Computational models of cortical processing, with an emphasis on the visual system. Applications of principles in neuroengineering; neural prostheses, neuromorphic systems and biomimetics. Course includes a computer simulation laboratory. Lab required.

ECBM E6070-6079x or y Topics in neuroscience and deep learning
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): the instructor's permission. Selected advanced topics in neuroscience and deep learning. Content varies from year to year, and different topics rotate through the course numbers 6070 to 6079.

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

BMEN E6301y Modeling of biological tissues with finite elements
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MECE E6422, or ENME E6315, or equivalent. Structure-function relations and linear/nonlinear constitutive models of biological tissues: anisotropic elasticity, viscoelasticity, porous media theories, mechano-electrochemical models, infinitesimal and large deformations. Emphasis on the application and implementation of constitutive models for biological tissues into existing finite element software packages. Model generation from biomedical images by extraction of tissue geometry, inhomogeneity and anisotropy. Element-by-element finite element solver for large-scale image based models of trabecular bone. Implementation of tissue remodeling simulations in finite element models.

BMEN E6400x Analysis and quantification of medical images
3 pts. Lect: 3. Not offered in 2024–2025.
Novel methods of mathematical analysis applied to problems in medical imaging. Design requirements for screening protocols, treatment therapies, and surgical planning. Sensitivity and specificity in screening mammography and chest radiographs, computer aided diagnosis systems, surgical planning in orthopaedics, quantitative analysis of cardiac performance, functional magnetic resonance imaging, positron emission tomography, and echocardiography data.

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

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

BMEN E6510y Stem cell, genome engineering, and regenerative medicine
3 pts. Lect: 3. Professors Tsang, Egli, and Vunjak-Novakovic.
Prerequisite(s): Biology, Cell Biology, BMEN E4001 or BMEN E4002. General lectures on stem cell biology followed by student presentations and discussion of primary literature. Themes presented include: basic stem cell concepts; basic cell and molecular biological characterization of endogenous stem cell populations; concepts related to reprogramming; directed differentiation of stem cell populations; use of stem cells in disease modeling or tissue replacement/repair; clinical translation of stem cell research.

BMEN E6520x Instructive biomaterials
3 pts. Lect: 3. Professor Arinzeh
Covers biomaterials that are instructive or have been designed or engineered to be instructive;

structure-function-property relationships in natural and synthetic biomaterials. Advances in understanding of material properties emphasized; including electroactivity, chemical, mechanical, geometry/architecture, and the modification of material surfaces and context of their effect on biological function. Evolving field of smart biomaterials discussed. Exercises/demonstrations using materials characterization equipment conducted.

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

BMEN E9100x or y Master's research
1–6 pts. Members of the faculty.
Candidates for the M.S. degree may conduct an investigation of some problem in biomedical engineering. No more than 6 points in this course may be counted for graduate credit.

BMEN E9500x or y Doctoral research
1–6 pts. Members of the faculty.
Doctoral candidates are required to make an original investigation of a problem in biomedical engineering, the results of which are presented in the dissertation.

BMEN E9700x or y Biomedical engineering seminar
0 pts. Sem: 1. Professors Danino, Juchem, and Olson.
All matriculated graduate students are required to attend the seminar as long as they are in residence. No degree credit is granted. The seminar is the principal medium of communication among those with biomedical engineering interests within the University. Guest speakers from other institutions, Columbia faculty, and students within the department who are advanced in their studies frequently offer sessions.

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

BMEN E9900x or y Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate in biomedical engineering or applied biology may be required to register for this course in every term after the student's coursework has been completed and until the dissertation has been a

CHEMICAL ENGINEERING

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Chemical engineering is a highly interdisciplinary field, focused on the study and design of chemical systems from the molecular to the process, system, and global scales. Practicing chemical engineers are in charge of the development and production of diverse materials and processes in traditional chemical industries as well as many emerging new areas. Chemical engineers in industry guide the passage of the product from the laboratory to the marketplace, from ideas and prototypes to functioning articles and processes, from theory to reality. Chemical engineering research is broader still, applying the principles of chemical engineering to the study and design of systems in biochemistry or environmental science, energy, advanced materials, and more.

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

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

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

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

Facilities for Teaching and Research

The Department of Chemical Engineering provides access to state-of-the-art research instrumentation and computational facilities for its undergraduate and graduate students, postdoctoral associates, and faculty. The recently renovated chemical engineering undergraduate laboratory features equipment including a Waters HPLC system, a SpectraMax spectrophotometer, a rotating disk electrode and potentiostat, a fixed bed adsorption unit, a solar cell/electrolyzer/fuel cell apparatus, flow and temperature control equipment, an IR camera, two PhyMetrix 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 laboratory facilities exist in the Columbia Electrochemical Energy Center, the Soft Materials laboratory, and the Columbia Genome Center.

Chemical engineering students, faculty, and research staff also have access to shared NMR, MRI, photochemical, spectroscopic, and mass spectrometry facilities in the Department of Chemistry.

UNDERGRADUATE PROGRAM

Chemical Engineering

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

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

Upon graduation, we expect our students to have:

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

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

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

The tables on pages 82 and 83 spell out the core course requirements, which are split between courses emphasizing engineering science and those emphasizing practical and/or professional aspects of the discipline. Throughout, skills required of practicing engineers are developed (e.g., writing and presentation skills, competency with computers).

The table on page 83 also shows that a significant fraction of the junior-senior program is reserved for electives, both technical and nontechnical. Twenty-one points (7 courses) of technical electives are included in the junior and senior year requirements. Technical electives are science and/or technology based and feature quantitative analysis. Generally, technical electives must be 3000 level or above but there are a few exceptions including: *PHYS UN1403, PHYS UN2601, BIOL UN2005, BIOL UN2006, BIOL UN2501, and CHEM UN2444. A full list of approved technical elective courses in each category can be found on the departmental website or obtained from the departmental advisers.* The technical electives are subject to the following constraints:

- **1 Thermodynamics Elective:** One technical elective must fall within the category "thermodynamics electives": Chemical engineering courses with 50% or more content related to thermodynamics. Examples include: CHAP E4120, CHEN E4650, CHEN E4880.

- **1 Transport Elective:** One technical elective must fall within the category "transport electives": Chemical engineering courses with 50% or

CHEMICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0)	MATH UN2030 (3) ODE **or** APMA E2101 (3)
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	Lab UN1494 (3) Lab UN3081 (2)	
CHEMISTRY (three tracks, choose one)	UN1403 (4) **and** Lab UN1500 (3) UN1604 (4) UN2045 (4)	UN1404 (4) UN1507 (3) UN2046 (4) **and** Lab UN1507 (3)	UN2443 (4)	
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES			One core humanities elective (3–4 points)[1]	Three core humanities electives (11 points)[1]
CHEM. ENG. REQUIREMENT	CHEN E1000 (1) Chemical engineering for humanity		CHEN E2100 (3) Material and energy balances	CHEN E3020 (3) Analysis of chem. eng. problems
COMPUTER SCIENCE		ENGI E1006 (3)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			
TOTAL POINTS[2]	17	17	17	17

[1] Four core humanities electives should be taken as follows: In Semester III, HUMA CC1001or COCI CC1101 (4) or any initial course in one of the Global Core sequences offered by the College (3–4); in Semester IV, HUMA CC1002 or COCI CC1102 (4) or ASCM UN2002 or the second course in the Global Core sequence elected in Semester III (3–4); also in Semester IV, ECON UN1105 (4) with UN1155 recitation (0) and either HUMA UN1121 or UN1123 (3).

[2] Taking the first track in each row and E1102 in Semester II.

more content related to transport phenomena (fluid mechanics, heat transfer, or mass transfer). Examples include: CHEN E4150, CHEN E4201, CHEN E4600, CHEN E4630.

- **1 Chemical Engineering Elective:** One upper-level technical course with the designator BMCH, CHEN, CHEE, CHAP, or MECH with significant engineering content
- **2 SEAS Electives outside Chemical Engineering:** Two upper-level technical courses with significant engineering content
- **2 Advanced Science Electives**: The remaining two technical elective courses must comprise "advanced science" coursework, which includes the natural sciences and certain engineering coursework. At least one of these courses must be taken outside of SEAS (e.g., in a science department at Columbia). Qualifying engineering courses are determined by Chemical Engineering department advisers.

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

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

CHEMICAL ENGINEERING: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
MATHEMATICS			MATH elective (3)[1]		
PHYSICAL EDUCATION[4]			UN1001 (1)		UN1002 (1)
REQUIRED COURSES		CHEN E3110 (3) Transp. phenomena, I CHEE E3010 (3) Principles of chem. eng. thermodynamics I	CHEN E3230 (3) Reaction kinetics and reactor design CHEN E4140 (3) Eng. separations processes	CHEN E4500 (4) Process and product design, I	
REQUIRED LABS		Adv natural science lab (3)[2]		CHEN E4300 (3) Chem. eng. process control and safety	CHEN E3810 (3) Chem. eng. lab
REQUIRED ELECTIVES	**NONTECH**	3 points	3 points	3 points	
	TECH[3]	3 points	3 points	6 points	9 points
TOTAL POINTS (normal track)		15	16	16	13

[1] Math elective options include APMA E3101, MATH UN2010, APMA E3102, APMA E4150, APMA E4300, STAT GU4001, or another course approved by the major adviser.

[2] Total of 3 points required. Choose from CHEM UN2493 (1.5), CHEM UN2496 (1.5), CHEM UN2543 (3), CHEM UN2545 (3), CHEM UN3085(3), BIOL 2501 (3), EEEB 3015 (3), or another course approved by the major adviser.

[3] See the bulletin text for technical elective requirements.

[4] May be taken in any semester.

the departmental website.

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

Requirements for a Minor in Chemical Engineering

See page 209.

GRADUATE PROGRAMS

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

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

M.S. Degree

The requirements are (1) the core courses: (i) math core: Mathematical methods in chemical engineering (CHEN E4010), (ii) transport core: Transport phenomena, III (CHEN E4110) or Transport in fluid mixtures (CHEN E4112), (iii) kinetics core: Advanced chemical kinetics (CHEN E4130) or Surface reactions and kinetics (CHEN E4235), and (iv) thermo core: Advanced chemical engineering thermodynamics (CHEN E4130) or Statistical mechanics (CHAP E4120); and (2) 18 points of 4000-level or higher courses, approved by the graduate coordinator or research adviser, of which up to 6 may be Master's research (CHEN 9400). Students with undergraduate preparation in physics, chemistry, biochemistry, pharmacy, and related fields may enroll in the scientist-to-engineer (S2E) program that leads to the master's degree in chemical engineering. This program requires an extra 6 credits associated with two mandatory Essentials classes (CHEN E4001 and E4002) that are used to ease the transition into chemical engineering.

Doctoral Degrees

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

COURSES IN CHEMICAL ENGINEERING

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

CHEN E1000x Chemical engineering for humanity
1 pt. Lect: 1. Professor Obermeyer.
Introduction to the role of Chemical Engineering in addressing grand challenges facing humanity. Address challenges illustrating the important role that Chemical Engineers play in solving societal problems, including those related to climate change, biotechnology and medicine, clean energy, and sustainable manufacturing of chemicals and materials.

CHEN E2100x Material and energy balances
3 pts. Lect: 3. Professor Chen.
Prerequisite(s): First-year chemistry and physics, or equivalent. Serves as an introduction to the chemical engineering profession. Students are exposed to concepts used in the analysis of chemical engineering problems. Rigorous analysis of material and energy balances on open and closed systems is emphasized. An introduction to important processes in the chemical and biochemical industries is provided.

CHEE E3010x Principles of chemical engineering thermodynamics
3 pts. Lect: 3. Professor Simunovic.
Prerequisite(s): CHEM UN1403 or equivalent. Teaches the formal relationships in the physical world, connecting the fundamental principles with the basis of chemical engineering practice. Topics include the first and second laws of thermodynamics, concepts such as energy and entropy, the equations that relate heat to other forms of energy, properties of ideal and real gases, fluids, single and multicomponent systems, phase and chemical equilibria, and the practical implications of these phenomena to systems from the molecular scale to the living world.

CHEN E3020y Analysis of chemical engineering problems
3 pts. Lect: 1.5. Lab: 1.5. Professor Urban.
Prerequisite(s): A Python course. Corequisite(s): Ordinary differential equations. Advance chemical-engineering problem-solving skills through computational tools (primarily developed in Excel or Python). Examples include thermodynamics, transport phenomena, and chemical kinetics. Project based, emphasizing data analysis and report writing. Unstructured collaboration with peers is highly encouraged. Requisite numerical methods and Chemical Engineering concepts are introduced.

CHEN E3110x Principles of transport phenomena
3 pts. Lect: 3. Professor Boyce.
Prerequisite(s): mechanics, vector calculus, ordinary differential equations. Mechanistic and mathematical description of the engineering fundamentals of heat and mass transport and fluid mechanics based on mass, momentum and energy balances from the molecular to the continuum to the industrial device scale. Problems and applications will focus on energy, biological and chemical systems and processes.

CHEN E3230y Reactor kinetics/reactor design
3 pts. Lect: 3. Professor Williams.
Prerequisite(s): CHEE E3010. Reaction kinetics, applications to the design of batch and continuous reactors. Multiple reactions, non-isothermal reactors. Analysis and modeling of reactor behavior.

BMCH E3500y Transport in biological systems
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEM UN2443 and MATH UN2030. Corequisite(s): BIOL UN2005. Convective and diffusive movement and reaction of molecules in biological systems. Kinetics of homogeneous and heterogeneous reactions in biological environments. Mechanisms arid models of transport across membranes. Convective diffusion with and without chemical reaction. Diffusion in restricted spaces. Irreversible thermodynamic approaches to transport and reaction in biological systems.

CHEN E3810y Chemical engineering and applied chemistry lab
3 pts. Lab: 3. Professor Ju.
Prerequisite(s): CHEN E2100, E3230, E4300, or instructor's permission. Emphasizes active, experiment-based resolution of open-ended problems involving use, design, and optimization of equipment, products, or materials. Under faculty guidance students formulate, carry out, validate, and refine experimental procedures, and present results in oral and written form. Develops analytical, communications, and cooperative problem-solving skills in the context of problems that span from traditional, large scale separations and processing operations to molecular level design of materials or products. Sample projects include scale up of apparatus, process control, chemical separations, microfluidics, surface engineering, molecular sensing, and alternative energy sources. Safety awareness is integrated.

CHEN E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

CHEN E3900x and y Undergraduate research project
1–6 pts. Members of the faculty.
Candidates for the B.S. degree may conduct an investigation of some problem in chemical engineering or applied chemistry or carry out a special project under the supervision of the staff. Credit for the course is contingent upon the submission of an acceptable thesis or final report. No more than 6 points may be counted toward the satisfaction of the B.S. degree requirements.

CHEN E3999x, y, or s Undergraduate fieldwork
1–2 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from adviser. Restricted to CHEN undergraduate students. Provides work experience on chemical engineering in relevant intern or fieldwork experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed internship/study program. A written report describing the experience and how it relates to the chemical engineering core curriculum is required. Employer feedback on student performance and the quality of the report are the basis of the grade. May not be taken for pass/fail or audited. May not be used as a technical or nontechnical elective. May be repeated for credit, but no more than 3 points total of CHEN E3999 may be used for degree credit.

CHEN E4001x Essentials of chemical engineering—A
3 pts. Lect: 3. Professor Chen.
Prerequisite(s): First-year chemistry and physics, vector calculus, ordinary differential equations, and the instructor's permission. Part of an accelerated consideration of the essential chemical engineering principles from the undergraduate program, including topics from Mass and Energy balances, Process Control, and Transport I and II. While required for all M.S. students with Scientist to Engineer status, the credits from this course may not be applied toward any chemical engineering degree.

CHEN E4002x Essentials of chemical engineering—B
3 pts. Lect: 3. Professor Chen.
Prerequisite(s): First-year chemistry and physics, vector calculus, ordinary differential equations, and the instructor's permission. Part of an accelerated consideration of the essential chemical engineering principles from the undergraduate program, including topics from Chemical Engineering Thermodynamics, I and II, Chemical

and Biochemical Separations. Reaction Kinetics and Reactor Design. While required for all M.S. students with Scientist to Engineer status, the credits from this course may not be applied oward any chemical engineering degree.

CHEN E4010x and y Mathematical methods in chemical engineering
3 pts. Lect: 3. Professor Venkatasubramanian.
Prerequisite(s): CHEN E3230, or equivalent, or instructor's permission. Mathematical description of chemical engineering problems and the application of selected methods for their solution. General modeling principles, including model hierarchies. Linear and nonlinear ordinary differential equations and their systems, including those with variable coefficients. Partial differential equations in Cartesian and curvilinear coordinates for the solution of chemical engineering problems.

CHEN E4020x Protection of industrial and intellectual property
3 pts. Lect: 3. Professor Spall.
To expose engineers, scientists and technology managers to areas of the law they are most likely to be in contact with during their career. Principles are illustrated with various case studies together with active student participation.

CHEE E4050y Principles of industrial electrochemistry
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E3010 or equivalent. A presentation of the basic principle underlying electrochemical processes. Thermodynamics, electrode kinetics, and ionic mass transport. Examples of industrial and environmental applications illustrated by means of laboratory experiments: electroplating, refining, and winning in aqueous solutions and in molten salts; electrolytic treatment of wastes; primary, secondary, and fuel cells.

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

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

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

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

CHAP E4120y Statistical mechanics and computational methods
3 pts. Lect: 3. Professor O'Shaughnessy.
Prerequisite(s): Thermodynamics, statistics, or instructor's permission. Boltzmann's entropy hypothesis and its restatement to calculate the Helmholtz and Gibbs free energies and the grand potential. Applications to interfaces, liquid crystal displays, polymeric materials, crystalline solids, heat capacity and electrical conductivity of crystalline materials, fuel cell solid electrolytes, rubbers, surfactants, molecular self-assembly, ferroelectricity. Computational methods for molecular systems. Monte Carlo (MC) and molecular dynamics (MD) simulation methods. MC method applied to liquid-gas and ferromagnetic phase transitions. Deterministic MD simulations of isolated gases and liquids. Stochastic MD simulation methods.

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

CHEN E4140y Engineering separations
3 pts. Lect: 3. Professor Esposito.
Prerequisite(s): CHEN E2100, E3110, and CHEE E3010 or instructor's permission. Design and analysis of unit operations employed in chemical engineering separations. Fundamental aspects of single and multistaged operations using both equilibrium and rate-based methods. Examples include distillation, absorption and stripping, extraction, membranes, crystallization, bioseparations, and environmental applications.

CHEN E4150y Computational fluid dynamics in chemical engineering
3 pts. Lect: 3. Not offered in 2024–2025.
Fundamentals of numerical algorithms for modeling dynamics of fluid flow computationally. Includes various approaches to discretize time and space on structured and unstructured grids with a variety of boundary conditions. Involves programming of basic CFD codes in MATLAB or Python to test example problems in fluid mechanics with different discretization schemes. Uses open-source software OpenFOAM to investigate more complex geometries and numerical approaches. Introduction to simulation of multiphase flow. Course grade based on homework assignments and final project report and presentation.

CHEN E4180x Machine learning for biomolecular and cellular applications
3 pts. Lect: 3. Professor O'Shaughnessy.
Prerequisite(s): Knowledge of Python, elementary statistics, thermodynamics. Introduction to machine learning techniques with applications to biological systems, emphasizing cell-biological molecular mechanisms and applications, and computational simulation. Overview of biology. Introduction to biological neurons and neural networks, learning and memory. Parallels between biological and artificial neural networks. Deep neural networks are introduced, hands-on computational experience for students. Big data from experiments or computational simulations: machine learning to extract mechanisms, dimensional reduction. Machine learning applications include drug discovery, protein structure prediction, molecular coarse-graining for simulations, and acceleration of molecular dynamics simulations.

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

CHEN E4231x Solar fuels
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Graduate standing, CHEN E3230, or instructor's permission. Fundamentals and applications of solar energy conversion, especially technologies for conversion of sunlight into storable chemical energy or solar fuels. Topics include fundamentals of photoelectrochemistry, kinetics of solar fuels production, solar harvesting technologies, solar reactors, and solar thermal production of solar fuels. Applications include solar fuels technology for grid-scale energy storage, chemical industry, manufacturing, environmental remediation.

CHEN E4235x Surface reactions and kinetics
3 pts. Lect: 3. Professor Chen.
Fundamental concepts and techniques to describe electronic, structural, chemical, and catalytic properties of surfaces. Kinetics and thermodynamics in adsorption, reaction, desorption, and diffusion processes on surfaces. Effects of transport in modifying surface reaction kinetics. Applies basic concepts in the chemical engineering curriculum (mathematical modeling, reaction kinetics, thermodynamics, transport) to surface reactions.

CHEE E4252x Introduction to surface and colloid chemistry
3 pts. Lect: 3. Professors Farinato and Somasundaran.
Prerequisite(s): Elemental physical chemistry. The principles of surfaces and colloid chemistry critical to range of technologies indispensable to modern life. Surface and colloid chemistry has significance to life sciences, pharmaceuticals, agriculture, environmental remediation and waste management, earth resources recovery, electronics, advanced materials, enhanced oil recovery, and emerging extraterrestrial mining. Topics include: thermodynamics of surfaces, properties of surfactant solutions and surface films, electrokinetic phenomena at interfaces, principles of adsorption and mass transfer and modern experimental techniques. Leads to deeper understanding of interfacial engineering, particulate dispersions, emulsions, foams, aerosols, polymers in solution, and soft matter topics.

CHEN E4300x Chemical process control and process safety
3 pts. Lect: 1. Lab: 2. Professor McNeill.
Prerequisite(s): Material and energy balances. Ordinary differential equations including Laplace transforms. Reactor Design. An introduction to process control applied to chemical engineering through lecture and laboratory. Concepts include the dynamic behavior of chemical engineering systems, feedback control, controller tuning, and process stability. Introduction to the fundamentals of process safety and hazard analysis.

CHEN E4320y Molecular phenomena in chemical engineering
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E3010 or instructor's permission. Introduces a molecular-level understanding of topics in modern chemical engineering. It builds upon and validates the concepts presented in the rest of the chemical engineering curriculum via a molecular perspective.

CHBM E4321x The genome and the cell
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): BIOL UN2005, MATH UN2030. The utility of genomic information lies in its capacity to predict the behavior of living cells in physiological, developmental, and pathological situations. The effect of variations in genome structure between individuals within a species, including those deemed healthy or diseased, and among species, can be inferred statistically by comparisons of sequences with behaviors, and mechanistically, by studying the action of molecules whose structure is encoded within the genome. Examines known mechanisms that elucidate the combined effect of environmental stimulation and genetic makeup on the behavior of cells in homeostasis, disease states, and during development, and includes assessments of the probable effect of these behaviors on the whole organism. Quantitative models of gene translation and intracellular signal transduction will be used to illustrate switching of intracellular processes, transient and permanent gene activation, and cell commitment, development, and death.

CHEN E4325 Bioseparations
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): CHEN E2100 or CHEN E3230, or equivalent. Design and analysis of the concentration, recovery, and isolation of biological molecules relevant in biotechnology. The unit operations used in recovery and purification of biological molecules. Theory and design of filtration, microfiltration, centrifugation, cell disruption, extraction, adsorption, chromatography, precipitations, ultrafiltration, crystallization, and drying. Students will have an understanding of basic principles of downstream processing, design and operations of various unit operations used in recovery of biological products, examining traditional unit operations, as well as new concepts and emerging technologies that are likely to benefit biochemical product recovery in the future.

CHEN E4330y Advanced chemical kinetics
3 pts. Lect: 3. Professor Carneiro.
Prerequisite(s): CHEN E3230 or instructor's permission. Complex reactive systems, molecular view of reaction kinetics, reactions in liquid, reactions at surfaces, diffusion-reaction systems. Applications to the design of batch and continuous reactors.

CHEN E4380y Green chemical engineering and innovation
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEM UN1404, CHEN E2100, CHEM UN2444. Approaches used in chemistry and chemical engineering to design green, sustainable products and processes; focus of using the tenets of green chemistry as a means for chemical innovation. Technical and design practice and measuring the impacts of green and conventional approaches emphasized. Themes of business, regulatory, ethical, and social considerations relevant to chemical engineering practice.

CHEN E4400x Chemical process development
3 pts. Lect: 3. Professor Mattas.
Prerequisite(s): CHEN E2100 or equivalent or instructor's permission. Chemical engineering fundamentals as applied to process research, development, and manufacturing of pharmaceutical products. Course topics include: comprehensive overview of the biopharmaceutical business (therapeutic areas, markets, drug discovery, clinical development, commercialization), process research, creation, development, optimization, sustainability, green chemistry and engineering, safety (patient, process, and personnel), unit operations and associated calculations relevant to pharmaceutical processes, process scale-up, implementation, assessment, technology transfer, new technologies, economic analysis, drug product formulation and manufacturing, and regulatory considerations. Case studies and real-life examples are presented throughout the course.

CHEN E4410x Environmental control technology
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEN E3010 or the equivalent. Causes of pollution and effect on life. Legal aspects, OSHA and EPA rules. Pollution at home and at work; radon, fumes, and dust; ventilation, dust collection, carbon adsorption. Fuel and acid gases, smog and dispersion. Treatment of ground, saline, and wastewater. Primary and secondary (biological) treatment. Tertiary water treatment with membranes, ion exchange, carbon, and sieves. Solid hazardous waste. Visit New York City wastewater treatment plant.

CHEN E4444y Climate tech
3 pts. Lect: 2.5. Professor West.
Prerequisite(s): CHEE E3010. Scientific and economic analysis of real-world technologies for climate change mitigation and adaptation. Partner with students from the business school to assess and assigned technology based on technical viability, commercial opportunity, and impact on mitigating or adapting to climate change. Assigned technologies provided by the investment community to teams of four, with expectations for independent research on the technologies, with deliverables of written and oral presentations.

CHEN E4500x Process and product design, I
4 pts. Lect: 4. Professor Ratanalert.
Prerequisite(s): CHEN E2100, CHEN E4140. The practical application of chemical engineering principles for the design and economic evaluation of chemical processes and plants. Use of ASPEN Plus for complex material and energy balances of real processes. Students are expected to build on previous coursework to identify creative solutions to two design projects of increasing complexity. Each design project culminates in an oral presentation, and in the case of the second project, a written report.

CHEN E4501x and y Chemical engineering process safety
3 pts. Lect.: 3. Professor Bozic.
Aimed at seniors and graduate students. Provides classroom experience on chemical engineering process safety as well as Safety in Chemical

Engineering certification. Process safety and process control emphasized. Application of basic chemical engineering concepts to chemical reactivity hazards, industrial hygiene, risk assessment, inherently safer design, hazard operability analysis, and engineering ethics. Application of safety to full spectrum of chemical engineering operations.

CHEN E4510y Process and product design, II
4 pts. Lect: 4. Professor Ratanalert.
Prerequisite(s): CHEN E4500. Students carry out a semester long process or product design course. The project culminates with a formal written design report and a public presentation. Recitation section required.

CHEE E4530y Corrosion of metals
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E3010 or equivalent. The theory of electrochemical corrosion, corrosion tendency, rates, and passivity. Application to various environments. Cathodic protection and coatings. Corrosion testing.

CHEE E4550x Climate engineering
3 pts. Lect: 3. Professors McNeill and Steingart.
Critical analysis of proposed approaches for climate mitigation involving intentional modification of the environment (also known as climate engineering, or geoengineering), with a focus on solar radiation management and weather modification. Emphasis on technical basis, potential intentional and unintentional environmental impacts, cost benefit analysis, and design considerations. History, ethics, social dimensions, and governance of climate engineering and climate engineering research.

CHEN E4580x Artificial intelligence in Chemical Engineering
3 pts. Lect: 3. Professor Venkatasubramanian.
Prerequisite(s): Background in chemical engineering and Python/MATLAB. Introduction to AI methods including knowledge-based systems and deep learning in the context of chemical engineering applications. Topics include chemical engineering modeling approaches, knowledge representation, symbolic reasoning and inference, knowledge-based systems, statistical data analysis, and machine learning methods such as clustering, neural networks, random forests, Bayesian networks, and directed evolution. Chemical engineering case studies in process monitoring, diagnosis, and control, process/product design, scheduling, and process hazards analysis. Development of hybrid models that combine first-principles knowledge of the underlying physics and chemistry with data-driven techniques and the development of causal mechanism-based models.

CHEN E4600y Aerosols
3 pts. Lect: 3. Professor McNeill.
Prerequisite(s): CHEN E3230 or instructor's permission. Aerosol impacts on indoor and outdoor air quality, health, and climate. Major topics include aerosol sources, physics, and chemistry; field and laboratory techniques for aerosol characterization; aerosol direct and indirect effects on climate; aerosols in biogeochemical cycles and climate engineering; health impacts, including exposure to ambient aerosols and transmission of respiratory disease.

CHEN E4610y Chemical product design
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E3010 and CHEM UN2443 or equivalent, or instructor's permission. Application of chemical and engineering knowledge to the design of new chemical products. Relationships between composition and physical properties. Strategies for achieving desired volumetric, rheological, phase equilibrium, thermal, and environmental behavior. Case studies, including separation solvents, blood substitutes, refrigerants, and aircraft deicing fluids.

CHEN E4620x Introduction to polymers and soft materials
3 pts. Lect: 3. Professor Durning.
Prerequisite(s): An elementary course in physical chemistry or thermodynamics. Organic chemistry, statistics, calculus and mechanics are helpful, but not essential. An introduction to the chemistry and physics of soft material systems (polymers, colloids, organized surfactant systems and others), emphasizing the connection between microscopic structure and macroscopic physical properties. To develop an understanding of each system, illustrative experimental studies are discussed along with basic theoretical treatments. High molecular weight organic polymers are discussed first (basic notions, synthesis, properties of single polymer molecules, polymer solution and blend thermodynamics, rubber and gels). Colloidal systems are treated next (dominant forces in colloidal systems, flocculation, preparation and manipulation of colloidal systems) followed by a discussion of self-organizing surfactant systems (architecture of surfactants, micelles and surfactant membranes, phase behavior).

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

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

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

CHEN E4670y Chemical engineering data analysis
3 pts. Lect: 3. Professor Bishop.
Prerequisite(s): CHEN E3230 or instructor's permission. Course is aimed at senior undergraduate and graduate students. Introduces fundamental concepts of Bayesian data analysis as applied to chemical engineering problems. Covers basic elements of probability theory, parameter estimation, model selection, and experimental design. Advanced topics such as nonparametric estimation and Markov chain Monte Carlo (MCMC) techniques are introduced. Example problems and case studies drawn from chemical engineering practice are used to highlight the practical relevance of the material. Theory reduced to practice through programming in Mathematica. Course grade based on midterm and final exams, biweekly homework assignments, and final team project.

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

CHEN E4700x Principles of genomic technologies
3 pts. Lect: 3. Professor Ju.
Prerequisite(s): Undergraduate-level biology, organic chemistry, and instructor's permission. Chemical and physical aspects of genome structure and organization, genetic information flow from DNA to RNA to protein. Nucleic acid hybridization and sequence complexity of DNA and RNA. Genome mapping and sequencing methods. The engineering of DNA polymerase for DNA sequencing and polymerase chain reaction. Fluorescent DNA sequencing and high-throughput DNA sequencer development. Construction of gene chip and micro array for gene expression analysis. Technology and biochemical approach for functional genomics analysis. Gene discovery and genetics database search method. The application of genetic database for new therapeutics discovery.

CHEN E4740x Biological transport and rate phenomena, II
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Any two of the following: CHEN E3110; BIOL UN2005; or BMCH E3500. Analysis of transport and rate phenomena in biological systems and in the design of biomimetic transport-reaction systems for technological and therapeutic applications. Modeling of homogeneous and heterogeneous biochemical reactions. The Bases of biological transport: roles of convection, ordinary diffusion, forced diffusion. Systems where reaction and transport interact strongly. Applications to natural and artificial tissue beds, tumor modeling, controlled release, natural and artificial organ function.

CHEN E4760y Genomics sequencing laboratory
3 pts. Lect: 1. Lab: 2. Not offered in 2024–2025.
Prerequisite(s): Undergraduate level biology, organic chemistry, and instructor's permission. The chemical, biological and engineering principles involved in the genomics sequencing process will be illustrated throughout the course for engineering students to develop the hands-on skills in conducting genomics research.

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

CHEN E4800x Protein engineering
3 pts. Lect: 3. Professor Banta.
Prerequisite(s): CHEN E3230, may be taken concurrently, or the instructor's permission. Fundamental tools and techniques currently used to engineer protein molecules. Methods used to analyze the impact of these alterations on different protein functions with specific emphasis on enzymatic catalysis. Case studies reinforce concepts covered, and demonstrate the wide impact of protein engineering research. Application of basic concepts in the chemical engineering curriculum (reaction kinetics, mathematical modeling, thermodynamics) to specific approaches utilized in protein engineering.

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

CHEN E4860x NMR for bio, soft, and energy materials
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): PHYS UN1401, CHEE E3010, or instructor's permission. Note: junior/senior undergraduates and graduate (M.S.) students only. Course focuses on the fundamentals of nuclear magnetic resonance (NMR) spectroscopy and imaging in fields ranging from biomedical engineering to electrochemical energy storage. Covers basic NMR theory, instrumentation (including in situ/operando setup), data interpretation, and experimental design to couple with other materials characterization strategies. Course grade based on problem sets, quizzes, and final project presentation.

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

CHEN E4880y Atomistic simulations for science and engineering
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): statistical mechanics or thermodynamics or instructor's permission. Aimed at senior undergraduates and graduate students. Covers atomistic simulation techniques for applications at interface of chemical engineering and materials science. Theoretical background of various simulation techniques ranging from empirical to first-principles approaches and hands-on experience in using state-of-the-art (free and open source) simulation software. Practical examples focus on inorganic materials mostly in crystalline solids, though methods taught are transferable to other materials classes. Course grades based on reports for practical assignments.

CHEN E4890 Biopharmaceuticals, entrepreneurship, and chemical engineering
3 pts. Lect: 3. Instructor to be announced.
Aimed at graduate students of Chemical Engineering. Examines the application of Chemical Engineering fundamentals and entrepreneurship in starting up a biopharmaceutical company and in developing a biopharmaceutical product. Serves as a description of the major stages of developing a biopharmaceutical product. Topics presented will include drug discovery, preclinical and clinical development, IP, manufacturing, and regulatory process. In addition, implementation of the lean startup methodology, business valuation, and financial considerations for a biopharmaceutical startup will be offered. Basic topics in the chemical engineering curriculum (reaction kinetics, mathematical modeling, unit operations, thermodynamics), as well as specific topics in developing biopharmaceuticals will be discussed in this course.

CHEN E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

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

CHEN E4910y Solid state chemistry in pharmaceutical development
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Thermodynamics (any) or General Chemistry. Fundamentals of solid state as related to pharmaceutical development, and is intended for junior and senior undergraduates and graduate students. Theoretical and practical aspects are covered, including segments on thermal and spectroscopic analytical instrumentation. Topics include crystal structure, polymorphism, crystallization processes, pharmaceutical properties, amorphous solids, solid state reactions, stability testing, solid oral formulation, particle size control, and dissolution testing. Connections between molecular structure, physical structure (e.g., particle size distribution), and product performance will be focus of class.

CHEN E4920y Pharmaceutical industry for engineers
3 pts. Lect: 3. Professor Moment.
Prerequisite(s): General Chemistry and Organic Chemistry. Overview of biopharmaceutical design, development, manufacturing, and regulatory requirements from an engineering perspective. Unit operations, equipment selection, and process development associated with small molecule, biologics, and vaccine manufacturing illustrated through examples, and quantitative engineering approaches applied as appropriate. Small molecules, biologics, vaccines, solid oral formulations, sterile processing, and design of experiments (DoE) treated along with a module on regulatory requirements.

CHEN E4930x Biopharmaceutical process laboratory
3 pts. Lect: 3. Professor Moment.
Prerequisite(s): Organic Chemistry Lab I, Undergraduate Organic Chemistry. Laboratory-based course intended for junior and senior undergraduate and graduate students interested in gaining hands-on experience in biopharmaceutical industry, including tableting, dissolution, disintegration, fermentation, chromatography, tangential flow filtration, mixing, and crystallization. Connections between process parameters, chemical and molecular properties, process parameters,

chemical and molecular properties, process performance, and product attributes illustrated through combination of lectures (given during lab time) experiments, and report writing.

CHEN E4999x and y Fieldwork
1.5–3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): M.S. student. Intended only for M.S. students. Provides work experience on chemical engineering in relevant intern or fieldwork experience as part of their program of study as determined by the instructor. A written report describing their experience and how it relates to the chemical engineering core curriculum is required. Employer feedback on student performance and the quality of the report are the basis of the grade. May not be taken for pass/fail credit or audited. Only 3 points of CHEN E4999 can be credited toward the M.S. degree. Furthermore, students who take CHEN E4999 can use only a maximum of 3 points of CHEN E 9400 in fulfillment of the M.S. degree.

CHEN E6050x Advanced electrochemistry
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Instructor's permission. An advanced overview of the fundamentals of electrochemistry, with examples taken from modern applications. An emphasis is placed on mass transfer and scaling phenomena. Principles are reinforced through the development of mathematical models of electrochemical systems. Course projects will require computer simulations. The course is intended for advanced graduate students, conducting research involving electrochemical technologies.

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

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

CHEE E6220y Equilibria and kinetics in hydrometallurgical systems
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Instructor's permission. An advanced overview of the fundamentals of electrochemistry, with examples taken from modern applications. An emphasis is placed on mass transfer and scaling phenomena. Principles are reinforced through the development of mathematical models of electrochemical systems. Course projects will require computer simulations. The course is intended for advanced graduate students, conducting research involving electrochemical technologies.

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

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

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

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

CHEN E9001x M.S. Chemical engineering colloquium
0 pts. Lect.: 1. Professor Chen.
Required for all M.S. students in residence in their first semester. Topics related to professional development and the practice of chemical engineering. No degree credits granted. Intended for M.S. students only.

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

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

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

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

CHEN E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
Open only to certified doctoral candidates. A candidate for the doctorate in chemical engineering may be required to register for this course in every term after the student's coursework has been completed, and until the dissertation has been accepted.

CIVIL ENGINEERING AND ENGINEERING MECHANICS

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MANAGER, CENTRIFUGE LABORATORY
Liming Li

SENIOR LABORATORY TECHNICIAN
Jamie Basirico

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

MISSION

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

Current Research Activities

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

Solid mechanics: mechanical properties of new and exotic materials, constitutive equations for geologic materials, failure of materials and components, properties of fiber-reinforced cement composites, damage mechanics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

FACILITIES

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

Computing

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

Laboratories

Robert A. W. Carleton Strength of Materials Laboratory

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

The Carleton Laboratory serves as the hub of instruction for classes offered

CIVIL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0)	APMA E2101 (3) Intro. to applied math.
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	Lab UN1494 (3) **or** chem. lab Lab UN3081 (2)	
CHEMISTRY	one-semester lecture (3–4): UN1403 **or** UN1404 **or** UN2045 **or** UN1604 Chem lab UN1500 (3) either semester **or** physics lab			
GEOLOGY	EESC UN1011 (4.5), UN2100 (4.5), UN2200 (4.5), UN2300 (4.5), or equivalent			
MECHANICS	ENME E3105 (4) either semester			
CIVIL ENGINEERING	CIEN E3000 (3) (Spring semester; recommended but not required)			CIEN E3004 (3) Urban infrastructure systems
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
COMPUTER SCIENCE	Computer Language: ENGI E1006 (3) or equivalent (any semester)			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

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

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

The Donald M. Burmister Soil Mechanics Laboratory

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

The Heffner Hydrologic Research Laboratory

The Heffner Laboratory is a facility for both undergraduate instruction and research in aspects of fluid mechanics, environmental applications, and water resources. The Heffner Laboratory houses the facilities for teaching the labora-

CIVIL ENGINEERING: THIRD AND FOURTH YEARS

		SEMESTER V	**SEMESTER VI**	**SEMESTER VII**	**SEMESTER VIII**
CORE REQUIRED COURSES		ENME E3113 (3) Mech. of solids ENME E3161 (4) Fluid mech.	CIEN E3125 (3) Structural design CIEN E3126 (1) Computer-aided struct. design CIEN E3141 (4) Soil mech.	CIEE E3111 (3.5) Uncertainty and risk in civil infrastructure systems CIEN E3129 (3) Proj. mgmt. for construction	CIEN E3128 (4) Design projects
CONCENTRATIONS	**GEOTECH ENG. (GE) OR STRUCT. ENG. (SE)**		ENME E3106 (3) Dynamics and vibrations ENME E3114 (4) Exper. mech. of materials CIEN E3121 (3) Struct. analysis	ENME E3332 (3) A first course in finite elements CIEN E3127 (3) Struct. design projects (SE) **or** CIEN E4241 (3) Geotech. eng. fund. (GE)	
	TECH ELECTIVES	3 points		3 points	9 points
	CIVIL ENG. AND CONSTR. MGMT.		ENME E3114 (4) Exper. mech. of materials CIEN E3121 (3) Struct. analysis **or** EACE E3250 (3) Hydrosystems eng.	CIEN E4133 (3) Capital facility planning and financing CIEN E3127 (3) Struct. design projects **or** CIEN E4241 (3) Geotech. eng. fund.	CIEN E4131 (3) Princ. of constr. tech.
	TECH ELECTIVES	6 points		3 points	6 points
	WATER RES./ ENVIRON. ENG.		EACE E3255 (3) Environ. control / pollution EACE E3250 (3) Hydrosystems eng. CIEN E3303 (1) Independent studies	EAEE E4350 (3) Plan./mgmt. of urban hydro. systems.	EACE E4163 (3) Sust. water treat. / reuse EAEE E4009 (3) GIS-resource, envir., infra. mgmt.
	TECH ELECTIVES	6 points		3 points	6 points
NONTECH ELECTIVES		3 points	3 points	3 points	
TOTAL POINTS		13	21	18.5	13

ENGINEERING MECHANICS PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0)	APMA E2101 (3) Intro. to applied math.
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	Lab UN1494 (3) **or** chem. lab Lab UN3081 (2)	
CHEMISTRY	One-semester lecture (3–4): UN1403 **or** UN1404 **or** UN2045 **or** UN1604 Chem lab UN1500 (3) either semester or physics lab			
MECHANICS	ENME E3105 (4) any semester			
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102 **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
REQUIRED TECH ELECTIVES	(3) Student's choice, see list of first- and second-year technical electives			
COMPUTER SCIENCE	Computer Language: ENGI E1006 (3) or equivalent (any semester)			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

tory component of the *ENME E3161 Fluid Mechanics* course and includes multiple hydraulic benches with a full array of experimental modules.

The Eugene Mindlin Laboratory for Structural Deterioration Research

The Mindlin Laboratory has been developed for teaching and research dedicated to all facets of the assessment of structures, deterioration of structural performance and surface coatings, dynamic testing for earthquakes, and other applications. The commissioning of a state-of-the-art 150 kN Instron universal testing machine, a QUV ultraviolet salt spray corrosion system, a freeze-thaw tester, a Keyence optical microscope and surface analyzer have further expanded the Mindlin Laboratory's capabilities in material testing and characterization. The Mindlin Laboratory also serves as a state-of-the-art medium scale nondestructive structural health monitoring facility, allowing the conduct of research in the assessment of our nation's degrading civil infrastructure.

The Institute of Flight Structures

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

UNDERGRADUATE PROGRAMS

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

ENGINEERING MECHANICS: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
CORE REQUIRED COURSES		ENME E3113 (3) Mech. of solids ENME E3161 (4) Fluid mechanics APMA E3101 (3) Applied math., I	APMA E3102 (3) Applied math., II ENME E3106 (3) Dynamics and vibrations ENME E3114 (4) Experimental mech. CIEN E3121 (3) Structural analysis	ENME E3332 (3) A first course in finite elements ENME E4202 (3) Advanced mech. ENME E4215 (3) Theory of vibrations	ENME E4113 (3) Advanced solids
ELECTIVES	**TECH**	3 points	6 points	6 points	9 points
	NONTECH			3 points	3 points
TOTAL POINTS		13	19	18	15

biological and energy systems.

Program Objectives

1. Graduates with a broad and fundamental technical base will be able to enter the professional civil engineering workforce either with a B.S. to develop specialized expertise by way of apprenticeship or through the increasingly common path of a specialized M.S.
2. Graduates with a firm foundation in the basic math, science, and engineering science that underlie all technological development will be well equipped to adapt to changing technology in the profession.
3. Graduates equipped with a broad technical background will be able to follow other technical or nontechnical career paths.
4. Graduates will practice their profession with effective writing and communication skills, with professional ethics, as well as with awareness of societal issues.

Student Outcomes

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

Engineering Mechanics

The prerequisites for this program are the courses listed in the First and Second Years Program (page 94) or their equivalents, with the provision that *ENME E3105: Mechanics* be taken in the sophomore year and that the student have obtained a grade of B or better.

Civil Engineering

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

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

Minor in Architecture

Civil engineering program students may want to consider a minor in architecture (see page 208-209).

GRADUATE PROGRAMS

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

Master of Science Degree Program

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

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

The Master of Science concentrations are:

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

Doctoral Degree Programs

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

In conjunction with their faculty adviser, doctoral degree students plan an appropriate course of study related to their area of focus within the department. Doctoral degree students must complete a minimum of 30 credits of graduate-level coursework beyond the M.S. degree. Candidates for the Eng. Sc.D. degree must also accumulate 12 credits in the departmental course CIEN E9800 Doctoral Research Instruction. In addition to coursework requirements, doctoral degree students must write a dissertation embodying original research under the sponsorship of their faculty adviser.

Major research thrusts for the doctoral degree programs include:

Computational mechanics
Multiscale mechanics
Poromechanics
Dynamics and vibrations
Infrastructure monitoring
Cementitious materials and concrete
Advanced infrastructure materials
Structural safety and reliability
Probabilistic mechanics
Sustainable/green infrastructure
Geomechanics
Fluid mechanics
Autonomous transportation
Disasters and natural hazards

Civil Engineering

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

- **Construction Engineering and Management:** capital facility planning and financing, strategic management, managing engineering and construction processes, construction industry law, construction techniques, managing civil infrastructure systems, civil engineering and construction entrepreneurship
- **Environmental Engineering and Water Resources:** transport of water-borne substances, hydrology, sediment transport, hydrogeology, and geoenvironmental design of containment systems
- **Geotechnical Engineering:** soil mechanics, foundation engineering, earth-retaining structures, slopes, and geotechnical earthquake engineering
- **Forensic (Structural) Engineering:** investigation and determination of the causes of structural failures of buildings, bridges, and other constructed facilities
- **Structural Engineering:** applications to steel and concrete buildings, bridges, and other structures

Engineering Mechanics

Programs in engineering mechanics offer comprehensive training in the principles of applied mathematics and continuum mechanics and in the application of these principles to the solution of engineering problems. The emphasis is on basic principles, enabling students to choose from among a wide range of technical areas. Students may work on problems in such disciplines as systems analysis, acoustics, and stress analysis, and in fields as diverse as transportation, environmental, structural, nuclear, and aerospace engineering. Program areas include:

- **Continuum mechanics:** solid and fluid mechanics, theories of elastic and inelastic behavior, and damage mechanics
- **Vibrations:** nonlinear and random vibrations; dynamics of continuous media, of structures and rigid bodies, and of combined systems, such as fluid-structure interaction; active, passive, and hybrid control systems for structures under seismic loading; dynamic soil-structure interaction effects on the seismic response of structures
- **Random processes and reliability:** problems in design against failure under earthquake, wind, and wave loadings; noise, and turbulent flows; analysis of structures with random

properties
- **Fluid mechanics:** turbulent flows, two-phase flows, fluid-structure interaction, fluid-soil interaction, flow in porous media, computational methods for flow and transport processes, and flow and transport in fractured rock under mechanical loading
- **Computational mechanics:** finite element and boundary element techniques, symbolic computation, and bioengineering applications.

A flight structures program is designed to meet the needs of industry in the fields of high-speed and space flight. The emphasis is on mechanics, mathematics, fluid dynamics, flight structures, and control. The program is a part of the Guggenheim Institute of Flight Structures in the department. Specific information regarding degree requirements is available in the department office.

COURSES IN CIVIL ENGINEERING

See also Courses in Engineering Mechanics at the end of this section.

CIEN E3000y The art of structural design
3 pts. Lect: 3. Professor Deodatis.
Basic scientific and engineering principles for the design of buildings, bridges, and other parts of the built infrastructure. Application of principles to analysis and design of actual large-scale structures. Coverage of the history of major structural design innovations and of the engineers who introduced them. Critical examination of the unique aesthetic/artistic perspectives inherent in structural design. Consideration of management, socioeconomic, and ethical issues involved in design and construction of large-scale structures. Introduction to recent developments in sustainable engineering, including green building design and adaptable structural systems.

CIEN E3004x Urban infrastructure systems
3 pts. Lect: 3. Professor Schlaepfer.
Introduction to: (a) the infrastructure systems that support urban socioeconomic activities and (b) fundamental system design and analysis methods. Coverage of water supply, transportation, buildings, and energy infrastructure, as well as their interdependencies. Emphasis upon the process that these systems serve, the factors that influence their performance, the basic mechanisms that govern their design and operation, and the impacts that they have regionally and globally. Student teams complete a design/analysis project on a large-scale urban development site in New York City with equal emphasis given to water resources/environmental engineering, geotechnical engineering, and construction engineering and management topics.

CIEN E3010y Introduction to construction: case studies
3 pts. Lect: 3. Professor Odeh.
Prerequisite(s): Instructor's permission. Introduces basic principles of how builders construct different types of projects. Shows detailed weekly cases on construction processes for infrastructure as well as building projects. Cases show major differences in constructing different types of projects and highlight challenges/solutions faced by project team during construction phase. Projects covered include: Tunnels, Bridges, Skyscrapers, Neighborhood Development, Mega Programs, Airports, and Education. Detailed examples of real case studies of iconic national and international projects. Includes site visits to active construction projects.

CIEE E3111x Uncertainty and risk in civil infrastructure systems
3.5 pts. Lect: 3. Professor Deodatis.
Prerequisite(s): Working knowledge of calculus. Introduction to basic probability; hazard function; reliability function; stochastic models of natural and technological hazards; extreme value distributions; statistical inference methods; Monte Carlo simulation techniques; fundamentals of integrated risk assessment and risk management; topics in risk-based insurance; case studies involving civil infrastructure systems, environmental systems, mechanical and aerospace systems, construction management.

CIEN E3121y Structural analysis
3 pts. Lect: 3. Professor Feng.
Methods of structural analysis. Trusses, arches, cables, frames; influence lines; deflections; force method; displacement method; computer applications.

CIEN E3125y Structural design
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite(s): ENME E3113. Design criteria for varied structural applications, including buildings and bridges; design of elements using steel, concrete, masonry, wood, and other materials.

CIEN E3126y Computer-aided structural design
1 pt. Lect: 1. Lab: 1. Instructor to be announced.
Corequisite(s): CIEN E3125. Introduction to software for structural analysis and design with lab. Applications to the design of structural elements and connections. Lab required.

CIEN E3127x Structural design projects
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite(s): CIEN E3125 and E3126 or the instructor's permission. Design of steel members in accordance with AISC 360: moment redistribution in beams; plastic analysis; bearing plates; beam-columns: exact and approximate second-order analysis; design by the Effective Length method and the Direct Analysis method. Design of concrete members in accordance with ACI 318: bar anchorage and development length, bar splices, design for shear, short columns, slender columns. AISC/ASCE NSSBC design project: design of a steel bridge in accordance with National Student Steel Bridge Competition rules; computer simulation and design by using SAP2000.

CIEN E3128y Design projects
4 pts. Lect: 4. Professor Panayotidi.
Prerequisite(s): CIEN E3125 and E3126. Capstone design project in civil engineering. This project integrates structural, geotechnical and environmental/water resources design problems with construction management tasks and sustainability, legal and other social issues. Project is completed in teams, and communication skills are stressed. Outside lecturers will address important current issues in engineering practice. Every student in the course will be exposed with equal emphasis to issues related to geotechnical engineering, water resources/environmental engineering, structural engineering, and construction engineering and management.

CIEN E3129x Project management for construction
3 pts. Lect: 3. Professor Chang.
Prerequisite(s): Senior standing in Civil Engineering or instructor's permission. Introduction to Project Management for design and construction processes. Elements of planning, estimating, scheduling, bidding, and contractual relationships. Computer scheduling and cost control. Critical path method. Design and construction activities. Field supervision.

CIEN E3141x Soil mechanics
4 pts. Lect: 3. Lab 3. Professor Ling.
Prerequisite(s): ENME E3113. Index properties and classification; compaction; permeability and seepage; effective stress and stress distribution; shear strength of soil; consolidation; slope stability.

EACE E3250y Hydrosystems engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): CHEN E3110 or ENME E3161 or equivalent, SIEO W3600 or equivalent, or instructor's permission. A quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for nonpoint source pollution. Spatial hydrologic analysis using GIS and watershed models. Note: This course is to be joint listed with EAEE and replaces the previous CIEN 3250.

EACE E3255y Environmental control and pollution reduction systems
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): EAEE E3200 or ENME E3161 or MECE E3100. Review of engineered systems for prevention and control of pollution. Fundamentals of material and energy balances and reaction kinetics. Analysis of engineered systems to address environmental problems, including solid and hazardous waste, and air, water, soil and noise pollution. Life cycle assessments and emerging technologies.

CIEE E3260y Engineering for community development
3 pts. Lect: 3. Professors Newman and Matthews.
Introduction to the challenges and realities of implementing design solutions with high-risk, low-resource communities in urban and rural settings in both developed and developing countries. History and theory of international development toward preparing globally responsible and informed professionals. Real-world examples of development work across technical sectors including water, sanitation, energy, health, communication technology, shelter, food systems, and environment. Role of engineering in achieving the Sustainable Development Goals. Course projects follow a Design for Impact process resulting in an engineering design, an action plan, and the identification of indicators for impact evaluation.

CIEN E3303x and y Independent studies in civil engineering for juniors
1–3 pts. By conference. Members of the faculty.
A project on civil engineering subjects approved by the chair of the department.

CIEN E3304x and y Independent studies in civil engineering for seniors
1–3 pts. By conference. Members of the faculty.
A project on civil engineering subjects approved by the chair of the department.

CEEM E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Research training course. Recommended in preparation for laboratory-related research.

CIEN E3999x, y or s Fieldwork
1–2 pts. Instructor to be announced.
Prerequisite(s): Obtained internship and approval from faculty adviser. CEEM undergraduate students only. Written application must be made prior to registration outlining proposed internship/study program. Final reports required. May not be taken for pass/fail credit or audited. International students must also consult with the International Students and Scholars Office.

CIEN E4010x Transportation engineering
3 pts. Lect: 3. Not offered in 2024–2025.
An overview of the planning, design, operation, and construction of urban highways and mass transportation systems. Transportation planning and traffic studies; traffic and highway engineering; rapid transit and railroad engineering.

CEOR E4011x Infrastructure systems optimization
3 pts. Lect: 3. Professor Di.
Prerequisite(s): Basic linear algebra. Basic probability and statistics. Engineering economic concepts. Basic spreadsheet analysis and programming skills. Subject to instructor's permission. Infrastructure design and systems concepts, analysis, and design under competing/conflicting objectives, transportation network models, traffic assignments, optimization, and the simplex algorithm.

CIEN E4011y Big data analytics in transportation
3 pts. Lect: 3. Professor Di.
Prerequisite(s): ENME E3105 or instructor's permission. Major elements of transportation analytics. Develop basic skills in applying fundamentals of data analytics to transportation data analysis. Apply coding languages (e.g., MATLAB, Python) and visualization tools (e.g., Excel, Carto, R, Processing) to analyze transportation data. Infer policy implications from analytics results.

CIEN E4012y Sustainable Urban Systems Engineering
3 pts. Lect: 3. Professor Schlaepfer.
Prerequisite(s): Basic linear algebra. Basic probability theory and statistics. Basic programming skills. Introduction to urban data analytics (analysis and visualization of new types of ‘big’ urban data, statistical tools for urban data analysis, machine learning methods, data privacy). Conceptualization of cities as complex adaptive systems (coarse-graining of urban dynamics, network models for infrastructure interdependencies, agent-based urban simulation). Integrated urban infrastructure systems design (basic design solutions for coupled, people-centric, and climate-resilient civil infrastructure systems, Monte Carlo simulations for infrastructure scenario generation).

CIEN E4021x Elastic and plastic analysis of structures
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CIEN E3121 or the equivalent. Overview of classical indeterminate structural analysis methods (force and displacement methods), approximate methods of analysis, plastic analysis methods, collapse analysis, shakedown theorem, structural optimization.

CIEN E4022y Bridge design and management
3 pts. Lect: 3. Professor Yanev.
Prerequisite(s): CIEN E3125 or the equivalent. Bridge design history, methods of analysis, loads: static, live, dynamic. Design: allowable stress, ultimate strength, load resistance factor, supply/demand. Steel and concrete superstructures: suspension, cable stayed, prestressed, arches. Management of the assets, life-cycle cost, expected useful life, inspection, maintenance, repair, reconstruction. Bridge inventories, condition assessments, data acquisition and analysis, forecasts. Selected case histories and field visits.

CIEN E4100x Earthquake and wind engineering
3 pts. Lect: 3. Professors Balsamo and Spyridaki.
Prerequisite(s): ENME E3106 or the equivalent. Basic concepts of seismology. Earthquake characteristics, magnitude, response spectrum, dynamic response of structures to ground motion. Base isolation and earthquake-resistant design. Wind loads and aeroelastic instabilities. Extreme winds. Wind effects on structures and gust factors.

ECIA W4100y Management and development of water systems
3 pts. Lect: 3. *Professors Gentine and Lall.*
Decision analytic framework for operating, managing, and planning water systems, considering changing climate, values, and needs. Public and private sector models explored through U.S.-international case studies on topics ranging from integrated watershed management to the analysis of specific projects for flood mitigation, water and wastewater treatment, or distribution system evaluation and improvement.

CIEE E4111x Uncertainty and risk in civil infrastructure systems
3 pts. Lect: 3. Professor Deodatis.
Prerequisite(s): Working knowledge of calculus. Introduction to basic probability, hazard function, reliability function, stochastic models of natural and technological hazards, extreme value distributions, Monte Carlo simulation techniques, fundamentals of integrated risk assessment and risk management, topics in risk-based insurance, case studies involving civil infrastructure systems, environmental systems, mechanical and aerospace systems. Not open to undergraduate students.

CIEE E4116x Energy harvesting
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ENME E3114 or equivalent, or instructor’s permission. Criterion of energy harvesting, identification of energy sources. Theory of vibrations of discrete and continuous system, measurement and analysis. Selection of materials for energy conversion, piezoelectric, electromagnetic, thermoelectric, photovoltaic, etc. Design and characterization, modeling and fabrication of vibration, motion, wind, wave, thermal gradient, and light energy harvesters; resonance phenomenon, power electronics and energy storage and management. Applications to buildings, geothermal systems, and transportation. To alternate with ENME E4115.

CIEN E4129x and y Managing engineering and construction processes
3 pts. Lect: 3. Professors Odeh and McManus
Prerequisite(s): Graduate standing in Civil Engineering, or instructor’s permission. Introduction to the principles, methods and tools necessary to manage design and construction processes. Elements of planning, estimating, scheduling, bidding and contractual relationships. Valuation of project cash flows. Critical path method. Survey of construction procedures. Cost control and effectiveness. Field supervision.

CIEN E4130x Design of construction systems
3 pts. Lect: 3. Professor Tirolo.
Prerequisite(s): CIEN E3125 or the equivalent, or the instructor’s permission. Introduction to the design of systems that support construction activities and operations. Determination of design loads during construction. Design of excavation support systems, earth retaining systems, temporary supports and underpinning, concrete formwork and shoring systems. Cranes and erection systems. Tunneling systems. Instrumentation and monitoring. Students prepare and present term projects.

CIEN E4131x and y Principles of construction techniques
3 pts. Lect: 3. Professors Odeh and Pilla.

Prerequisite(s): CIEN E4129 or equivalent. Current methods of construction, cost-effective designs, maintenance, safe work environment. Design functions, constructability, site and environmental issues.

CIEN E4132x Prevention and resolution of construction disputes
3 pts. Lect: 3. Professors Chertoff and Serkin.
Prerequisite(s): CIEN E4129 or equivalent. Contractual relationships in the engineering and construction industry and the actions that result in disputes. Emphasis on procedures required to prevent disputes and resolve them quickly and cost-effectively. Case studies requiring oral and written presentations.

CIEN E4133x and y Capital facility planning and financing
3 pts. Lect: 3. Professors Chang and Asgari.
Prerequisite(s): CIEN E4129 or equivalent. Planning and financing of capital facilities with a strong emphasis upon civil infrastructure systems. Project feasibility and evaluation. Design of project delivery systems to encourage best value, innovation and private sector participation. Fundamentals of engineering economy and project finance. Elements of life cycle cost estimation and decision analysis. Environmental, institutional, social and political factors. Case studies from transportation, water supply and wastewater treatment.

CIEN E4134y Construction industry law
3 pts. Lect: 3. Professor Charney.
Prerequisite(s): Graduate standing or the instructor's permission. Practical focus upon legal concepts applicable to the construction industry. Provides sufficient understanding to manage legal aspects, instead of being managed by them. Topics include contractual relationships, contract performance, contract flexibility and change orders, liability and negligence, dispute avoidance/resolution, surety bonds, insurance and site safety.

CIEN E4135y Strategic management in engineering and construction
3 pts. Lect: 3. Professor Bell.
Core concepts of strategic planning, management and analysis within the construction industry. Industry analysis, strategic planning models and industry trends. Strategies for information technology, emerging markets and globalization. Case studies to demonstrate key concepts in real-world environments.

CIEN E4136y Entrepreneurship in engineering and construction
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Instructor's permission. Capstone practicum where teams develop strategies and business plans for a new enterprise in the engineering and construction industry. Identification of attractive market segments and locations; development of an entry strategy; acquisition of financing, bonding, and insurance; organizational design; plans for recruiting and retaining personnel; personnel compensation/incentives. Invited industry speakers. Priority given to graduate students in Construction Engineering and Management.

CIEN E4137y Managing civil infrastructure systems
3 pts. Lect: 3. Professor Chang.
Prerequisite(s): IEOR E4003, CIEN E4133, or equivalent. Examination of the fundamentals of infrastructure planning and management, with a focus on the application of rational methods that support infrastructure decision-making. Institutional environment and issues. Decision-making under certainty and uncertainty. Capital budgeting and financing. Group decision processes. Elements of decision and finance theory.

CIEN E4138y Real estate finance for construction management
3 pts. Lect: 3. Professor Riordan.
Prerequisite(s): IEOR E2261, CIEN E3129 or permission of instructor. Introduction to financial mechanics of public and private real estate development and management. Working from perspectives of developers, investors and taxpayers, financing of several types of real estate and infrastructure projects are covered. Basics of real estate accounting and finance, followed by in-depth studies of private, public, and public/private-partnership projects and their financial structures. Focused on U.S.-based financing, with some international practices introduced and explored. Financial risks and rewards, and pertinent capital markets and their financing roles. Impacts and incentives of various government programs, such as LEED certification and solar power tax credits. Case studies provide opportunity to compare U.S. practices to several international methods.

CIEN E4139x Theory and practice of virtual design and construction
3 pts. Lect: 3. Professor Polat.
Prerequisite(s): CIEN E4129 or instructor's permission. History and development of Building Information Modeling (BIM), its uses in design and construction, and introduction to the importance of planning in BIM implementation. Role of visual design and construction concepts and methodologies, including integrated project delivery form in architecture, engineering, and construction industries from project design, cost estimating, scheduling, coordination, fabrication, installation, and financing.

CIEN E4140x Environmental, health, and safety concepts in construction processes
3 pts. Lect: 3. Professor Haining.
Prerequisite(s): Graduate standing in Civil Engineering and Engineering Mechanics. A definitive review of and comprehensive introduction to construction industry best practices and fundamental concepts of environmental health and safety management systems (EH&S) for the construction management field. How modern EH&S management system techniques and theories not only result in improved safe work environments but ultimately enhance operational processes and performance in construction projects.

CIEN E4141y Public-private partnerships in global infrastructure development
3 pts. Professor Chang.
Graduate students only. Delivery of infrastructure assets through Public-Private Partnerships (PPP). Value for Money analysis. Project organization. Infrastructure sector characterization. Risk analysis, allocation, and mitigation. Monte Carlo methods and Real Options. Project finance and financing instruments. Case studies from transportation, water supply, and energy sectors.

CIEN E4142x International construction management: theory and practice
3 pts. Lect: 3. Professor Odeh.
Prerequisite(s): CIEN E4129 or instructor's permission. Complex global construction industry environment. Social, cultural, technological, and political risks; technical, financial, and contractual risk. Understanding of successful global project delivery principles and skills for construction professionals. Industry efforts and trends to support global operational mechanism. Global Case Studies. Engage with industry expert professionals. Student group projects with active ongoing global initiatives.

CIEN E4144x Real estate land development engineering
3 pts. Lect: 3. Professors Leventis, O'Connor, and Vitolano.
Comprehensive review of various engineering disciplines in the process of real estate land development. Engineering disciplines covered include civil, infrastructure, transportation planning, environmental planning, permitting, environmental remediation, geotechnical, and waterfront/marine. Overview of land use and environmental law, architecture and urban planning, as related to land development. Discussion of how these subjects affect decisions—cost, schedule, programming—involved in real estate development. Note: Graduate and senior undergraduate students only. Third-year undergraduate students with instructor's permission.

CIEN E4145x Applied use of AEC data
3 pts. Lect: 2.5. Professors Diaz Gonzalez and Jeon.
Digital transformation optimizes day-to-day operations to provide maximum performance in Architecture, Engineering, and Construction (AEC) workflows. Focuses on broadening knowledge of AEC data leading to building data management. Use of open data sets from the design, construction, and operations of buildings to learn and practice data management and its applied use. Major technical topics include Project Management Information System (PMIS) and Facility Management (FM), leading to Digital Twin data management, data processing, and data visualization.

CIEN E4146y Advanced AEC data management
3 pts. Lect: 3. Professors Diaz Gonzalez and Jeon.
Prerequisite(s): CIEN E4145. Focused on broadening knowledge of AEC data management. Use of industry data sets from the design, construction, and operations of buildings to learn and practice data management and solve problems by aggregating industry data and

creating data-driven reports in a dashboard format. Exploration of industry data through ELT (Extract, Load, Transform) Services. Hands-on learning experiences through a series of workshops and case studies. Course will guide where predictive analysis is performed and how it is used for Project Management Information System (PMIS) and Facility Management (FM), leading to Digital Twin data management, data processing, and data visualization.

CIEN E4148x and y Construction engineering and management industry field studies
3 pts. Lect: 1. Professors Stigliano and Karachaliou.
Expose students to various aspects of project management in the construction industry, enhance learning experience with real-world challenges and prepare for internships and future employment. Run for two semesters. First semester focuses on Traditional Project Management, and the second semester focuses on Agile Project Management. For class project, development of a Project Management Plan (PMP) and an Operations Dashboard based on real-life examples of contracts (traditional project management) and operational excellence initiatives (agile project management).

ACHE W4149x The Roman art of engineering: traditions of planning, construction, and innovation
3 pts. Lect: 3. Professors Chang and de Angelis.
Prerequisite(s): CIEN E3000 and CIEN E3129 or equivalent required for engineering students. Interdisciplinary study of ancient Roman engineering and architecture in a course co-created between Arts & Sciences and Engineering. Construction principles, techniques, and materials: walls, columns, arches, vaults, domes. Iconic Roman buildings (Colosseum, Pantheon, Trajan's Column) and infrastructure (roads, bridges, aqueducts, baths, harbors, city walls). Project organization. Roman engineering and society: machines and human labor; engineers, architects, and the army; environmental impact. Comparisons with current practice as well as cross-cultural comparisons with other pre-modern societies across the globe.

CIEN E4150y Leadership in Design and Construction
3 pts. Lect: 1. Professor Odeh.
Introduces and employs various tools, concepts, and analytical frameworks to enhance students' ability to dene and analyze leadership issues. In-depth analysis of the leadership literature and practical situational immersion using industry case studies. Multiple guest lecturers from the private and public sectors throughout the semester. Term project exploring leadership challenges in the design and construction industry.

EACE E4163y Sustainable water treatment and reuse
3 pts. Lect: 3. Professor Knowles.
Prerequisite(s): Introductory chemistry (with laboratory) and fluid mechanics. Fundamentals of water pollution and wastewater characteristics. Chemistry, microbiology, and reaction kinetics. Design of primary, secondary, and advanced treatment systems. Small community and residential systems.

CIEN E4210x Forensic structural engineering
3 pts. Lect: 3. Professors Jampole and Morgan.
Prerequisite(s): Working knowledge of structural analysis and design; graduate student standing or instructor's permission. Review of significant failures, civil/structural engineering design and construction practices, ethical standards and the legal positions as necessary background to forensic engineering. Discussion of standard-of-care. Study of the process of engineering evaluation of structural defects and failures in construction and in service. Examination of the roles, activities, conduct and ethics of the forensic consultant and expert witness. Students are assigned projects of actual cases of nonperformance or failure of steel, concrete, masonry, geotechnical, and temporary structures, in order to perform, discuss, and report their own investigations under the guidance of the instructor.

CIEN E4212y Structural failures: cases, causes, lessons learned
3 pts. Lect: 3. Professors Jampole and Morgan.
Prerequisite(s): A course each in engineering materials, structural analysis, concrete design, steel design, soil mechanics and foundations, and construction; graduate student standing or instructor's permission. The nature and causes of structural failures and the lessons learned from them; insight into failure investigation in the practice of forensic structural engineering. Case histories of actual failures of real-life structures during construction and in service are introduced, examined, analyzed, and discussed. Students are assigned documented cases of failures of structures of various types and materials to review, discuss, and, in some cases, to conduct investigations of the causes and responsibilities. Students are required to prepare written reports and make oral presentations of selected cases.

CIEN E4213x Elastic and inelastic buckling of structures
3 pts. Lect: 3. Instructor to be announced.
Stability of framed structures in the elastic and inelastic ranges. Lateral buckling of beams. Torsional buckling of compression members. Buckling of plates of plate-stiffener combinations. Linear stability analysis of cylindrical shells and discussion of its limitations. Discussion of the semiempirical nature of the elastoplastic relations used in the case of plates and shells.

CIEN E4226y Advanced design of steel structures
3 pts. Lect: 3. Professors Aly and Mosquera.
Prerequisite(s): CIEN E3125 or equivalent. Review of loads and structural design approaches. Material considerations in structural steel design. Behavior and design of rolled steel, welded, cold-formed light-gauge, and composite concrete/steel members. Design of multistory buildings and space structures.

CIEN E4232x Advanced design of concrete structures
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite(s): CIEN E3125 or equivalent. Design of concrete beams for combined torsion, shear and flexure; moment-curvature relation; bar cut-off locations; design of two-way slabs; strut-and-tie method for the design of deep beams and corbels; gravity and shear wall design; retaining wall design.

CIEN E4233y Design of large-scale bridges
3 pts. Lect: 3. Professor Zoli.
Prerequisite(s): CIEN E3121 or equivalent, and CIEN E3127 or equivalent. Design of large-scale and complex bridges with emphasis on cable-supported structures. Static and dynamic loads, component design of towers, superstructures and cables; conceptual design of major bridge types including arches, cable stayed bridges and suspension bridges.

CIEN E4234y Design of large-scale building structures
3 pts. Lect: 3. Professors Ghisbain, Gottlieb, Malsch, and Tomasetti.
Prerequisite(s): CIEN E3121 and E3127. Modern challenges in the design of large-scale building structures will be studied. Tall buildings, large convention centers, and major sports stadiums present major opportunities for creative solutions and leadership on the part of engineers. This course is designed to expose the students to this environment by having them undertake the complete design of a large structure from initial design concepts on through all the major design decisions. The students work as members of a design team to overcome the challenges inherent in major projects. Topics include overview of major projects, project criteria and interface with architecture, design of foundations and structural systems, design challenges in the post 9/11 environment, and roles, responsibilities, and legal issues.

CIEN E4235x Multihazard design of structures
3 pts. Lect: 3. Professors Daddazio and Mosquera.
Prerequisite(s): CIEN E3125 or E4232 or instructor's permission. Fundamental considerations of wave mechanics; design philosophies; reliability and risk concepts; basics of fluid mechanics; design of structures subjected to blast; elements of seismic design; elements of fire design; flood considerations; advanced analysis in support of structural design.

CIEN E4236y Design of prestressed concrete structures
3 pts. Lect: 3. Professor Panayotidi.
Prerequisite(s): CIEN E4232 or instructor's permission. Properties of materials used in prestressed concrete; pretensioning versus posttensioning; loss of prestress due to elastic shortening, friction, anchorage slip, shrinkage, creep and relaxation; full versus partial prestressing; design of beams for flexure, shear, and torsion; method of load balancing; anchorage zone design; calculation of deflection by the lump-sum and incremental time-step methods; continuous beams; composite construction; prestressed slabs and columns.

CIEN E4237x Architectural design, computation, and method
3 pts. Lect: 1.5. Lab: 1.5. Not offered in 2024–2025.
Prerequisite(s): CIEN E3121 or equivalent. CIEN E3125 or equivalent. Integrated methods of design and structural analysis between engineering and architecture. Lectures on historical precedents on material use, structural inventiveness, and social importance. Labs on drafting and modeling software; physical modeling techniques and virtual reality visualization.

CIEN E4241x Geotechnical engineering fundamentals
3 pts. Lect: 3. Professor Yang.
Prerequisite(s): CIEN E3141 or instructor's permission. Bearing capacity and settlement of shallow and deep foundations; earth pressure theories; retaining walls and reinforced soil retaining walls; sheet pile walls; braced excavation; slope stability.

CIEN E4242x Geotechnical earthquake engineering
3 pts. Lect: 3. Professor Ling.
Prerequisite(s): CIEN E3141 or equivalent. Seismicity, earthquake intensity, propagation of seismic waves, design of earthquake motion, seismic site response analysis, in situ and laboratory evaluation of dynamic soil properties, seismic performance of underground structures, seismic performance of port and harbor facilities, evaluation and mitigation of soil liquefaction and its consequences. Seismic earth pressures, slopes stability, safety of dams and embankments, seismic code provisions and practice. To alternate with E4244.

CIEN E4243x Foundation engineering
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CIEN E3141 or equivalent. Conventional types of foundations and foundation problems: subsurface exploration and testing. Performance of shallow and deep foundations and evaluation by field measurements. Case histories to illustrate typical design and construction problems. To alternate with CIEN E4246.

CIEN E4244y Geosynthetics and applications
3 pts. Lect: 3. Professor Ling.
Prerequisite(s): CIEN E4241 or the equivalent. Properties of geosynthetics. Geosynthetic design for soil reinforcement. Geosynthetic applications in solid waste containment system.

CIEN E4245x Design of underground transportation projects
3 pts. Lect: 3. Professor Abrahams.
Prerequisite(s): Familiarity with computer aided design, reinforced concrete design, geotechnical engineering, and the use of common computer applications is required. Introduction to management of complex underground transportation projects with a focus on design and construction of different types of tunnel, including cut and cover tunnel, mechanized tunneling, and immersed tube tunnel. Review of multidisciplinary aspects of transportation projects including: mechanical, civil, environmental, electrical engineering, project controls, community outreach, and real estate acquisition.

CIEN E4246x Earth retaining structures
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CIEN E3141. Retaining structures, bulkheads, cellular cofferdams, and braced excavations. Construction dewatering and underpinning. Instrumentation to monitor actual performances. Ground improvement techniques, including earth reinforcement, geotextiles, and grouting. To alternate with CIEN E4243.

CIEN E4247y Design of large-scale deep foundation systems
3 pts. Lect.: 3. Not offered in 2024–2025.
Prerequisite(s): CIEN E3141. Focus on deep foundations in difficult conditions and constraints of designing foundations. Design process from the start of field investigations through construction and the application of deep foundations.

EACE E4250x or y Hydrosystems engineering
3 pts. Lect: 3. *Professors Gentine and Kelly*.
Prerequisite(s): CHEN E3110 or ENME E3161 or equivalent, or instructor's permission. Quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for non-point source pollution. Spatial hydrologic analysis using GIS and watershed models.

EACE E4252y Foundations of environmental engineering
3 pts. Lect: 3. Professor Chandran.
Prerequisite(s): CHEM UN1403, or equivalent; ENME E3161 or equivalent, or instructor's permission. Engineering aspects of problems involving human interaction with the natural environment. Review of fundamental principles that underlie the discipline of environmental engineering, i.e. constituent transport and transformation processes in environmental media such as water, air, and ecosystems. Engineering applications for addressing environmental problems such as water quality and treatment, air pollution emissions, and hazardous waste remediation. Presented in the context of current issues facing the practicing engineers and government agencies, including legal and regulatory framework, environmental impact assessments, and natural resource management

CIEN E4253x Computational Solid Mechanics with AI
3 pts. Lect: 3. Professor Sun.
Prerequisite(s): ENME3332E OR ENGI1006E. Knowledge of Python. MECE E6422 and COMS W4995 strongly recommended but not required. Theoretical, computational, and data-driven/machine learning techniques to derive, test, and validate computer models for solid mechanics (e.g., soil, rubber, and metals). Machine learning and data-driven simulations enabled by deep learning.

CIEE E4257x Groundwater contaminant transport and remediation
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ENME E3161 and EACE E3250 or instructor's permission. Sources and types of groundwater contamination. Groundwater hydrology. Groundwater contaminant fate and transport. Flow and transport in the unsaturated zone. Nonaqueous phase liquids and multiphase flow. Physical and numerical models for contaminant transport. Characterization and assessments of contaminated sites. Groundwater remediation alternatives. Regulations.

CIEE E4260x Urban ecology studio
3 pts. Lect: 2.5. Lab 2.5. Not offered in 2024–2025.
Prerequisite(s): Senior undergraduate or graduate student standing and instructor's permission. Conjoint studio run with the Graduate School of Architecture, Planning and Preservation (GSAPP) that explores solutions to problems of urban density. Engineering and GSAPP students will engage in a joint project that addresses habitability and sustainability issues in an urban environment, and also provides community service. Emphasis will be on the integration of science, engineering and design within a social context. Interdisciplinary approaches and communication will be stressed.

CIEN E4300x Infrastructural materials
3 pts. Lect: 3. Not offered in 2024–2025.
Basic concepts of materials science for civil infrastructure materials. Relate composition, structure, processing to engineering properties (e.g., strength, modulus, ductility-malleability, durability). Materials covered include stone, brick, terra cotta, concrete, cast stone, metals, and wood. Overview of sourcing and production, identification, fabrication, chemical, physical and mechanical properties.

PLCE W4444x The future city: transforming urban infrastructure
3 pts. Lect: 3. Professors Smyth and Ascher.
Introduces students to technological innovations that are helping cities around the world create healthier, safer, more equitable, and more resilient futures. Focus on architecture, urban design, real estate development, structural, civil and mechanical engineering, data analytics, and smart communication technologies. Course covers five distinct sectors in the field of urban infrastructure, including transportation and mobility, buildings, power, sanitation, and communications.

CEEM E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

CIEN E4995x and y Topics in civil engineering
3 pts. Lect: 3. Members of the faculty.
Special topics sections arranged as the need and availability arises. Topics are usually offered on a one-time basis. May be repeated for credit.

CIEN E4999x and y Fieldwork
1–2 pts. Members of the faculty
Prerequisite(s): Instructor's written approval. May be repeated for credit, but no more than 3 total points may be used for degree credit. Only for Civil Engineering and Engineering Mechanics graduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation required. May not be taken for pass/fail credit or audited.

CIEN E6246y Advanced soil mechanics
3 pts. Lect: 3. Professor Ling.
Prerequisite(s): CIEN E3141. Stress-dilatancy of sand; failure criteria; critical state soil mechanics; limit analysis; finite element method and case histories of consolidation analysis.

CIEN E6248x Experimental soil mechanics
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CIEN E3141. Advanced soil testing, including triaxial and plane strain compression tests; small-strain measurement. Model testing; application (of test results) to design.

CIEN E9101x and y–S9101 Civil engineering research
1–4 pts. Members of the faculty.
Advanced study in a specialized field under the supervision of a member of the department staff. Before registering, the student must submit an outline of the proposed work for approval of the supervisor and the department chair.

CIEN E9500x and y Departmental seminar
0 pts. Professor Ling.
All doctoral students are required to attend the department seminar as long as they are in residence. No degree credit is granted.

CIEN E9800x and y–S9800 Doctoral research instruction
3–12 pts. May be taken for 3, 6, 9, or 12 points, dependent on instructor's permission.
A candidate for the Eng.Sc.D. degree in civil engineering must register for 12 points of doctoral research instruction. Registration in CIEN E9800 may not be used to satisfy the minimum residence requirement for the degree.

CIEN E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the student's coursework has been completed and until the dissertation has been accepted.

COURSES IN ENGINEERING MECHANICS

See also Courses in Civil Engineering at the beginning of this section.

ENME E3105x and y Mechanics
4 pts. Lect: 4. Professors Hone and Kougioumtzoglou.
Prerequisite(s): PHYS UN1401, MATH UN1101, MATH UN1102, and MATH UN1201 or APMA E2000. Elements of statics; dynamics of a particle and systems of particles.

ENME E3106y Dynamics and vibrations
3 pts. Lect: 2. Professor Kidane.
Prerequisite(s): MATH UN1201 or APMA E2000, and APMA E2101. Corequisite(s): ENME E3105. Kinematics of rigid bodies; momentum and energy methods; vibrations of discrete and continuous systems; eigenvalue problems, natural frequencies and modes. Basics of computer simulation of dynamics problems using MATLAB.

ENME E3113x Mechanics of solids
3 pts. Lect: 3. Professor Betti.
Pre- or corequisite: ENME E3105 or equivalent. Stress and strain. Mechanical properties of materials. Axial load, bending, shear, and torsion. Stress transformation. Deflection of beams. Buckling of columns. Combined loadings. Thermal stresses.

ENME E3114y Experimental mechanics of materials
4 pts. Lect: 2. Lab: 3. Professor Kawashima.
Prerequisite(s): ENME E3113. Material behavior and constitutive relations. Mechanical properties of metals and cement composites. Structural materials. Modern construction materials. Experimental investigation of material properties and behavior of structural elements including fracture, fatigue, bending, torsion, buckling.

ENME E3161x Fluid mechanics
4 pts. Lect: 3. Lab: 3. Professor Giometto.
Prerequisite(s): ENME E3105 and ordinary differential equations. Fluid statics. Fundamental principles and concepts of flow analysis. Differential and finite control volume approach to flow analysis. Dimensional analysis. Application of flow analysis: flow in pipes, external flow, flow in open channels.

ENME E3332x A first course in finite elements
3 pts. Lect: 3. Professor Fish.
Prerequisite(s): Senior standing or instructor's permission. Recommended corequisite(s): differential equations. Focus on formulation and application of the finite element to engineering problems such as stress analysis, heat transfer, fluid flow, and electromagnetics. Topics include finite element formulation for one-dimensional problems, such as trusses, electrical and hydraulic systems; scalar field problems in two dimensions, such as heat transfer; and vector field problems, such as elasticity and finally usage of the commercial finite element program. Students taking ENME E3332 cannot take ENME E4332.

ENME E4113y Advanced mechanics of solids
3 pts. Lect: 3. Professor Yin.
Stress and deformation formulation in two-and three-dimensional solids; viscoelastic and plastic material in one and two dimension energy methods.

ENME E4114x Mechanics of fracture and fatigue
3 pts. Lect: 3. Professor Brügger.
Prerequisite(s): Undergraduate mechanics of solids course. Elastic stresses at a crack; energy and stress intensity criteria for crack growth; effect of plastic zone at the crack; fracture testing applications. Fatigue characterization by stress-life and strain-life; damage index; crack propagation; fail safe and safe life analysis.

EMME E4115x Micromechanics of composite materials
3 pts. Lect: 3. Professor Yin.
Prerequisite(s): ENME E4113 or instructor's approval. An introduction to the constitutive modeling of composite materials: Green's functions in heterogeneous media, Eshelby's equivalent inclusion methods, eigenstrains, spherical and ellipsoidal inclusions, dislocations, homogenization of elastic fields, elastic, viscoelastic and elastoplastic constitutive modeling, micromechanics-based models.

ENME E4202y Advanced mechanics
3 pts. Lect: 3. Professor Smyth.
Prerequisite(s): ENME E3105 or equivalent. Differentiation of vector functions. Review of kinematics. Generalized coordinates and constraint equations. Generalized forces. Lagrange's equations. Impulsive forces. Collisions. Hamiltonian. Hamilton's principle.

ENME E4212x Experimental solid mechanics
3 pts. Lect: 3. Professor Kidane.
Prerequisite(s): ENME E3113. Experimental techniques, including photoelasticity, strain measurements, digital image correlation, and other optics in stress analysis, emphasizing engineering applications. Fundamental concepts in solid mechanics and measurement science. Performance of high-quality experimental studies.

ENME E4214y Theory of plates and shells
3 pts. Lect: 3. Professor Dasgupta.
Prerequisite(s): ENME E3113. Static flexural response of thin, elastic, rectangular, and circular plates. Exact (series) and approximate (Ritz) solutions. Circular cylindrical shells. Axisymmetric and nonaxisymmetric membrane theory. Shells of arbitrary shape.

ENME E4215x Theory of vibrations
3 pts. Lect: 3. Professor Betti.
Frequencies and modes of discrete and continuous elastic systems. Forced vibrations-steady-state and transient motion. Effect of damping. Exact and approximate methods. Applications.

ENME E4332x Finite element analysis, I
3 pts. Lect: 3. Professor Waisman.
Prerequisite(s): Mechanics of solids, structural analysis, elementary computer programming (MATLAB) is recommended, linear algebra and ordinary differential equations. Direct stiffness approach for trusses. Strong and weak forms for one-dimensional problems. Galerkin finite element formulation, shape functions, Gauss quadrature, convergence. Multidimensional scalar field problems (heat conduction), triangular and rectangular elements, Isoparametric formulation. Multidimensional vector field problems (linear elasticity). Practical FE modeling with commercial software (ABAQUS). Computer implementation of the finite element method. Advanced topics. Not open to undergraduate students.

ENME E4363y Multiscale computational science and engineering
3 pts. Lect: 3. Professor Fish.

Prerequisite(s): ENME E4332, elementary computer programming, linear algebra. Introduction to multiscale analysis. Information-passing bridging techniques: among them, generalized mathematical homogenization theory, the heterogeneous multiscale method, variational multiscale method, the discontinuous Galerkin method and the kinetic Monte Carlo–based methods. Concurrent multiscale techniques: domain bridging, local enrichment, and multigrid-based concurrent multiscale methods. Analysis of multiscale systems.

ENME E6215x Principles and applications of sensors for structural health monitoring
3 pts. Lect: 2.5. Lab: 0.5. Not offered in 2024–2025.
Prerequisite(s): ENME E4215. Concepts, principles, and applications of various sensors for sensing structural parameters and nondestructive evaluation techniques for subsurface inspection, data acquisition, and signal processing techniques. Lectures, demonstrations, and hands-on laboratory experiments.

ENME E6216y Structural health monitoring
3 pts. Lect: 3. Professor Betti.
Prerequisite(s): ENME E4215 and ENME E4332. Principles of traditional and emerging sensors, data acquisition and signal processing techniques, experimental modal analysis (input-output), operational modal analysis (output-only), model-based diagnostics of structural integrity, long-term monitoring and intelligence maintenance. Lectures and demonstrations, hands-on laboratory experiments.

ENME E6220y Stochastic engineering mechanics
3 pts. Lect: 3. Professor Kougioumtzoglou.
Prerequisite(s): CIEE E4111 and ENME E4215 or instructor's permission. Review of random variables. Random process theory: stationary and ergodic processes, correlation functions and power spectra, non-stationary, non-white and non-Gaussian processes. Uncertainty quantification and simulation of environmental excitations and material/media properties, even when subject to limited/incomplete data: joint time-frequency analysis, sparse representations and compressive sampling concepts and tools. Stochastic dynamics and reliability assessment of diverse engineering systems: complex nonlinear/hysteretic behaviors and/or fractional derivative modeling. Emphasis on solution methodologies based on Monte Carlo simulation, statistical linearization, and Wiener path integral. Examples from civil, marine, mechanical, and aerospace engineering.

ENME E6315x Theory of elasticity
3 pts. Lect: 3. Not offered in 2024–2025.
Foundations of continuum mechanics. General theorems of elasticity. Application to stress analysis and wave propagation.

ENME E6320y Computational poromechanics
3 pts. Lect: 3. Professor Sun.
Prerequisite(s): ENME E3332 or instructor’s permission. A fluid infiltrating porous solid is a multiphase material whose mechanical behavior is significantly influenced by the pore fluid. Diffusion, advection, capillarity, heating, cooling, and freezing of pore fluid, buildup of pore pressure, and mass exchanges among solid and fluid constituents all influence the stability and integrity of the solid skeleton, causing shrinkage, swelling, fracture, or liquefaction. These coupling phenomena are important for numerous disciplines, including geophysics, biomechanics, and material sciences. Fundamental principles of poromechanics essential for engineering practice and advanced study on porous media. Topics include balance principles, Biot’s poroelasticity, mixture theory, constitutive modeling of path independent and dependent multiphase materials, numerical methods for parabolic and hyperbolic systems, inf-sup conditions, and common stabilization procedures for mixed finite element models, explicit and implicit time integrators, and operator splitting techniques for poromechanics problems.

ENME E6333y Finite element analysis, II
3 pts. Lect: 3. Professor Waisman.
Prerequisite(s): ENME E4332. FE formulation for beams and plates. Generalized eigenvalue problems (vibrations and buckling). FE formulation for time-dependent parabolic and hyperbolic problems. Nonlinear problems, linearization, and solution algorithms. Geometric and material nonlinearities. Introduction to continuum mechanics. Total and updated Lagrangian formulations. Hyperelasticity and plasticity. Special topics: fracture and damage mechanics, extended finite element method.

ENME E6364x Nonlinear computational mechanics
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ENME E4332 or equivalent, elementary computer programming, linear algebra. The formulations and solution strategies for finite element analysis of nonlinear problems are developed. Topics include the sources of nonlinear behavior (geometric, constitutive, boundary condition), derivation of the governing discrete equations for nonlinear systems such as large displacement, nonlinear elasticity, rate independent and dependent plasticity and other nonlinear constitutive laws, solution strategies for nonlinear problems (e.g., incrementation, iteration), and computational procedures for large systems of nonlinear algebraic equations.

ENME E6370y Turbulence theory and modeling
3 pts. Lect: 3. Professor Giometto.
Prerequisite(s): ENME E3161 or equivalent, Ordinary and partial differential equations. Turbulence phenomenology, spatial and temporal scales in turbulent flows, statistical description, filtering and Reynolds decomposition, equations governing the resolved flow, fluctuations and their energetics, turbulence closure problem for RANS and LES, two-equation turbulence models, and second-moment closures.

ENME E8310x Advanced continuum mechanics
3 pts. Lect: 3. Professor Dasgupta.
Prerequisite(s): MECE E6422 and E6423. Open to Ph.D. students and to M.S. students with instructor’s permission. Review of continuum mechanics in Cartesian coordinates; tensor calculus and the calculus of variation; large deformations in curvilinear coordinates; electricity problems and applications.

ENME E8320x Viscoelasticity and plasticity
4 pts. Lect: 3. Professor Dasgupta.
Prerequisite(s): ENME E6315 or equivalent, or instructor’s permission. Constitutive equations of viscoelastic and plastic bodies. Formulation and methods of solution of the boundary value, problems of viscoelasticity and plasticity.

ENME E8323y Nonlinear vibrations
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ENME E4215 or equivalent. Free and forced motion of simple oscillators with nonlinear damping and stiffness. Exact, perturbation, iteration, and graphical methods of solution. Stability of motion. Chaotic vibrations.

COURSES IN GRAPHICS

GRAP E4005y Computer graphics in engineering
3 pts. Lect: 3. Professor Dasgupta.
Prerequisite(s): Any programming language and linear algebra. Numerical and symbolic (algebraic) problem solving with Mathematica. Formulation for graphics application in civil, mechanical, and bioengineering. Example of two-and three-dimensional curve and surface objects in C++ and Mathematica; special projects of interest to electrical and computer science.

COMPUTER ENGINEERING PROGRAM

Administered by both the Electrical Engineering and Computer Science Departments through a joint Computer Engineering Committee. Student records are kept in the Electrical Engineering Department.

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PROGRAM CHAIR
Mingoo Seok
1012 CEPSR

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  Professor of Electrical Engineering
Gil Zussman,
  Professor of Electrical Engineerin

The computer engineering program is run jointly by the Computer Science and Electrical Engineering departments. It offers both B.S. and M.S. degrees.

The program covers some of engineering's most active, exciting, and critical areas, which lie at the interface between CS and EE. The focus of the major is on computer systems involving both digital hardware and software.

Some of the key topics covered are computer design (i.e., computer architecture); embedded systems (i.e., the design of dedicated hardware/software for cell phones, automobiles, robots, games, and aerospace); digital and VLSI circuit design; computer networks; design automation (i.e., CAD); and parallel and distributed systems (including architectures, programming, and compilers).

Students in the programs have two “home” departments. The Electrical Engineering Department maintains student records and coordinates advising appointments.

UNDERGRADUATE PROGRAM

This undergraduate program incorporates most of the core curricula in both electrical engineering and computer science so that students will be well prepared to work in the area of computer engineering, which substantially overlaps both fields. Both hardware and software aspects of computer science are included, and, in electrical engineering, students receive a solid grounding in circuit theory and in electronic circuits. The program includes several electrical engineering laboratory courses as well as the Computer Science Department's advanced programming course. Detailed lists of requirements can be found at compeng.columbia.edu.

Students will be prepared to work on all aspects of the design of digital hardware, as well as on the associated software that is now often an integral part of computer architecture. They will also be well equipped to work in the growing field of telecommunications. Students will have the prerequisites to delve more deeply into either hardware or software areas, and enter graduate programs in computer science, electrical engineering, or computer engineering. For example, they could take more advanced courses in VLSI, communications theory, computer architecture, electronic circuit theory, software engineering, or digital design.

Minors in electrical engineering and computer science are not open to computer engineering majors, due to excessive overlap.

Technical Electives

The Computer Engineering Program includes 15 points of technical electives. All must be 3000 level or above, technical, and must not have significant overlap with other courses taken for the major. Adviser approval of technical electives is required.

Most courses at the 3000 level or above offered by the Computer Science and Electrical Engineering departments are eligible, and up to two from outside those departments can be considered for approval as well. If a department advertises that one of its courses can be used as a technical elective that does not necessarily mean it will be approved as a technical elective in the computer engineering program. There must be sufficient technical content and computer engineering connection within the entire 15 points, so approval of some courses may depend on the other electives chosen. Economics courses cannot be used as technical electives. COMS

COMPUTER ENGINEERING PROGRAM: FIRST AND SECOND YEARS EARLY-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester	
				APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	UN1401 (3)	UN1402 (3)	Lab UN1494 (3) **or** chem. lab UN1500 (3)	
	UN1601 (3.5)	UN1602 (3.5)	Lab UN1494 (3) **or** chem. lab UN1500 (3)	
	UN2801 (4.5)	UN2802 (4.5)	Lab UN3081 (2) **or** chem. lab UN1500 (3)	
CHEMISTRY	one-semester lecture (3–4) UN1403 **or** UN1404 or UN2045 **or** UN1604 Lab UN1500 (3) either semester **or** physics lab UN1494 (3)			
CORE REQUIRED COURSES	ELEN E1201 (3.5) Intro. to elec. eng. (either semester)		ELEN E3801 (3.5) Signals and systems	COMS W3134 (3) **or** W3137 (4) Data structures CSEE W3827 (3) Fund. of computer sys.
REQUIRED LABS			ELEN E3084 (1) Signals and systems lab	ELEN E3082 (1) Digital systems lab
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES[2]			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
COMPUTER SCIENCE	ENGI E1006 (3)	COMS W1004 (3) **or** W1007 (3)	COMS W3203 (3) Discrete math.	
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (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 either APMA E3101, or MATH UN2010, or COMS W3251.

[2] Some of these courses can be postponed to the junior or senior year to make room for taking the required core computer engineering courses.

<table>
<tr><th colspan="6">COMPUTER ENGINEERING: THIRD AND FOURTH YEARS
EARLY-STARTING STUDENTS</th></tr>
<tr><th colspan="2"></th><th>SEMESTER V</th><th>SEMESTER VI</th><th>SEMESTER VII</th><th>SEMESTER VIII</th></tr>
<tr><td colspan="2" rowspan="2">CORE REQUIRED COURSES</td><td rowspan="2">IEOR E3658 (3)[1]
Probability
COMS W3157 (4)
Advanced programming
ELEN E3201 (3.5)
Circuit analysis</td><td>ELEN E3331 (3)
Electronic circuits
COMS W3261 (3)
Computer sci. theory</td><td colspan="2">COMS W4118 (3) Operating systems
or
COMS W4115 (3) Programming lang.</td></tr>
<tr><td colspan="3">(Choose 3 of 6)
CSEE W4119 (3) Computer networks, EECS E4321 (3) Digital VLSI circuits, CSEE W4823 (3) Advanced logic design, CSEE W4824 (3) Computer architecture, CSEE W4840 (3) Embedded systems, CSEE W4868 (3) System-on-chip platforms</td></tr>
<tr><td colspan="2">REQUIRED LABS</td><td>ELEN E3081 (1)
Circuit analysis lab</td><td>ELEN E3083 (1)
Electronic circuits lab</td><td></td><td></td></tr>
<tr><td rowspan="2">ELECTIVES</td><td>TECH[2]</td><td colspan="4">15 points required; see details within the text</td></tr>
<tr><td>NONTECH</td><td colspan="4">Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement)</td></tr>
<tr><td colspan="2">TOTAL POINTS[3]</td><td>17.5</td><td>17</td><td>15</td><td>15</td></tr>
</table>

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

[1] SIEO W3600, STAT GU4203, and STAT GU4001 can be used instead of IEOR E3658, but W3600 and GU4001 may not provide enough probability background for elective courses such as ELEN E3701. Students completing an economics minor who want such a background can take IEOR E3658 and augment it with IEOR E4307.

[2] 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.

[3] "Total points" assumes that 20 points of nontechnical electives and other courses are included.

W3101/W3102 courses, and not-very-technical courses within the school of engineering, cannot be used as technical electives either.

Starting Early

Students are strongly encouraged to begin taking core computer engineering courses as sophomores. They start with *ELEN E1201: Introduction to electrical engineering* in the second semester of their first year and may continue with other core courses one semester after that. For sample "early-starting" and "late-starting" programs, see the degree track charts. It must be emphasized that these charts present examples only; actual schedules may be customized in consultation with academic advisers.

GRADUATE PROGRAM

The Computer Engineering Program offers a course of study leading to the degree of Master of Science (M.S.). The basic courses in the M.S. program come from the Electrical Engineering and Computer Science Departments. Students completing the program are prepared to work (or study further) in such fields as digital computer design, digital communications, and the design of embedded computer systems.

Applicants are generally expected to have a bachelor's degree in computer engineering, computer science, or electrical engineering with at least a 3.2 GPA in technical courses. The Graduate Record Examination (GRE), General Test only, is required of all applicants.

Students must take at least 30 points of courses at Columbia University at or above the 4000 level. These must include at least 15 points from the courses listed below that are deemed core to computer engineering. Other courses may be chosen with the prior approval of a faculty adviser in the Computer Engineering Program.

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

COMPUTER ENGINEERING PROGRAM: FIRST AND SECOND YEARS
LATE-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester	
				APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	UN1401 (3)	UN1402 (3)	Lab UN1494 (3) **or** chem. lab UN1500 (3)	
	UN1601 (3.5)	UN1602 (3.5)	Lab UN1494 (3) **or** chem. lab UN1500 (3)	
	UN2801 (4.5)	UN2802 (4.5)	Lab UN3081 (2) **or** chem. lab UN1500 (3)	
CHEMISTRY	one-semester lecture (3–4) UN1403 **or** UN1404 **or** UN2045 **or** UN1604 Lab UN1500 (3) either semester **or** physics lab UN1494 (3)			
CORE REQUIRED COURSES	ELEN E1201 (3.5)[2] Intro. to elec. eng. (either semester)			
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
COMPUTER SCIENCE	ENGI E1006 (3)	COMS W1004 (3) **or** W1007 (3)	W3203 (3) Discrete math.	
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101, or MATH UN2010, or COMS W3251.

[2] Transfer and combined-plan students are expected to have completed the equivalent of the first- and second-year program listed above before starting their junior year. Note that this includes some background in discrete math (see COMS W3203) and 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.

COMPUTER ENGINEERING: THIRD AND FOURTH YEARS
LATE-STARTING STUDENTS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
CORE REQUIRED COURSES		IEOR E3658 (3)[1] Probability COMS W3134 (3) **or** W3137 (4) Data structures ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	COMS W3157 (4) Advanced programming ELEN E3331 (3) Electronic circuits COMS W3261 (3)[2] Models of comp. CSEE W3827 (3) Fund. of computer systems	COMS W4118 (3) Operating systems **or** COMS W4115 (3) Programming lang.	
				(Choose 3 of 6) CSEE W4119 (3) Computer networks, EECS E4321 (3) Digital VLSI circuits, CSEE W4823 (3) Advanced logic design, CSEE W4824 (3) Computer architecture, CSEE W4840 (3) Embedded systems, CSEE W4868 (3) System-on-chip platforms	
REQUIRED LABS		ELEN E3081 (1)[3] Circuit analysis lab ELEN E3084 (1)[3] Signals and systems lab	ELEN E3083 (1)[3] Electronic circuits lab ELEN E3082 (1)[3] Digital systems lab		
ELECTIVES	TECH[4]	15 points required; see details within the text			
	NONTECH	Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement)			
TOTAL POINTS[5]		15	18	15	18

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

[1] SIEO W3600, STAT GU4203, and STAT GU4001 can be used instead of IEOR E3658, but W3600 and GU4001 may not provide enough probability background for elective courses such as ELEN E3701. Students completing an economics minor who want such a background can take IEOR E3658 and augment it with IEOR E4307.

[2] COMS W3261 can be taken one semester later than pictured.

[3] If possible, ELEN E3081 and ELEN E3084 should be taken along with ELEN E3201 and ELEN 3801, respectively, and ELEN E3083 and ELEN E3082 taken with ELEN E3331 and CSEE W3827 respectively.

[4] The total points of technical electives is reduced to 12 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010, or COMS W3251. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can apply for this waiver, but the courses must have been at an advanced level for this to be considered.

[5] Assuming technical electives taken Semesters VII and VIII, and 9 points of nontechnical electives taken Semesters VI, VII, and VIII.

Core Computer Engineering Courses

CSEE W4119: Computer networks
CSEE W4140: Networking laboratory
EECS E4321: Digital VLSI circuits
EECS E4750: Heterogeneous computing for signal and data processing
EECS E4764: Iot—intelligent & connected sys.
CSEE W4823: Advanced logic design
CSEE W4824: Computer architecture
CSEE W4840: Embedded systems
CSEE W4868: Systems-on-chip platforms
EECS E4951: Wireless networks & systems
EECS E6180: Modeling & performance eval
EECS E6321: Adv. digital electronic circuits
COMS E6424: Hardware security
CSEE E6863: Formal verification of hardware/ software systems
CSEE E6868: Embedded scalable platforms
EECS E6890: Advanced computer networks (course number varies by semseter)
EECS E6897: Distributed storage systems
COMS W6998: Topics in computer science: Data center networks

The overall program must include at least 12 points of 6000-level *ELEN, EECS, CSEE*, or *COMS* courses (exclusive of seminars). No more than 9 points of research project may be taken for credit. No more than 3 points of a nontechnical elective (at or above the 4000 level and with adviser approval) may be included. A minimum GPA of at least 2.7 must be maintained, and all degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

COMPUTER SCIENCE

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Javad Ghaderi
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Henryk Wozniakowski
Yechiam Yemini

The function and influence of the computer is pervasive in contemporary society. Today's computers process the daily transactions of international banks, the data from communications satellites, the images in video games, and even the fuel and ignition systems of automobiles.

Computer software is as commonplace in education and recreation as it is in science and business. There is virtually no field or profession that does not rely upon computer science for the problem-solving skills and the production expertise required in the efficient processing of information. Computer scientists, therefore, function in a wide variety of roles, ranging from pure theory and design to programming and marketing.

The computer science curriculum at Columbia places strong emphasis both on theoretical computer science and mathematics and on applied aspects of computer technology. A broad range of upper-level courses is available in such areas as artificial intelligence, machine learning, computer graphics, computer vision, robotics, computational complexity and the analysis of algorithms, combinatorial methods, computer architecture, computer-aided digital design, computer communications, databases, mathematical models for computation, optimization, and software systems.

Laboratory Facilities

The department has a dedicated computing work space for students with dedicated workstations as well as audiovisual equipment for group meetings, specialized office hours, and small seminars. The department also has its own 120-seat lecture hall featuring flexible seating, a dedicated podium computer, and presentation equipment, as well as video conferencing capabilities.

The department maintains its own dedicated Data Center for computational research, storage, and administrative systems. It houses several computer clusters for research and student use and several hundred research systems, all supported by more than a petabyte of storage. Services offered to the department utilize virtual machines (VMWare supporting more than 500 instances) and containerization (100 Docker containers).

In addition, the department has numerous individual laboratories with specialized hardware dedicated to particular research areas, including, but not limited to, robotics, computer vision, computer networks, computer security, computer architecture, speech processing, machine learning, and natural language processing.

COMPUTER SCIENCE PROGRAM: FIRST AND SECOND YEARS STARTING FALL 2023[1]

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0)	
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	Chemistry or physics lab: PHYS UN1494 (3) **or** PHYS UN3081 (2) **or** CHEM UN1500 (3) **or** CHEM UN1507 (3) **or** CHEM UN3085 (4)	
CHEMISTRY/ BIOLOGY (choose one course)	CHEM UN1403 (3) **or** higher **or** EEEB UN2001 (4) **or** UN2005 (4) **or** higher either semester			
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES	ECON UN1105 (4) **and** UN1105 recitation (0) any semester			
			HUMA CC1001 **or** COCI CC1101 **or** Major Cultures (3–4)	HUMA CC1002 **or** COCI CC1102 **or** Major Cultures (3–4)
				HUMA UN1121 **or** UN1123 (3)
REQUIRED TECH ELECTIVES	ENGI E1006 Computing for EAS (3) either semester			
COMPUTER SCIENCE	COMS W1004 (3) or COMS W1007 (3) Intro to computer science		COMS W3134 (3) **or** COMS W3137 (4) Data structures **and** COMS W3203 (4) Discrete math	COMS W3157 (4) Adv. programming **and** linear algebra or probability/statistics requirement (see list of accepted courses)[1]
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

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[1] For program information before Fall 2023, please view the 2022–2023 Bulletin.

COMPUTER SCIENCE: THIRD AND FOURTH YEARS STARTING FALL 2023[1]

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES		CSEE W3827 (3) Fund. of comp. systems **and** COMS W3261 (3) Computer sci. theory **and** Linear Algebra **or** Probability/Statistics requirement (see list of accepted courses)			
ELECTIVES	**NONTECH**		3 points	6 points	3 points
	TECH	6 points	12 points	9 points	9 points
TOTAL POINTS		15	15	15	12

[1] For program information before Fall 2023, please view the 2022–2023 Bulletin.

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 to pursue their interests both in applications and in theoretical developments.

Practical experience is an essential component of the computer science program. Undergraduate students are often involved in advanced faculty research projects using state-of-the-art computing facilities. Qualified majors sometimes serve as consultants at Columbia University Information Technology (CUIT), which operates several labs with microcomputers and terminals available at convenient locations on the campus.

Upper-level students in computer science may assist faculty members with research projects, particularly in the development of software. Ongoing faculty projects include algorithmic analysis, computational complexity, software tool design, distributed computation, modeling and performance evaluation, computer networks, computer architecture, CAD for digital systems, computer graphics, programming environments, expert systems, natural language processing, computer vision, robotics, computational biology, computer security, multicomputer design, user interfaces, VLSI applications, artificial intelligence, combinatorial modeling, virtual environments, and microprocessor 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 with industry or government, or continue their education in graduate degree programs. Many choose to combine computer science with a second career interest by taking additional programs in business administration, medicine, or other professional studies.

For further information on the undergraduate computer science program, please see the home page and the Quick Guide at cs.columbia.edu/education/undergraduate.

The CS Major Requirements

The Undergraduate program requires at minimum 62 points (including ENGI E1006 as a prerequisite to the major) and is composed of four basic components: the **Computer Science Core** (7-8 courses), the **Area Foundation Courses** (4 courses), the **Computer Science Electives** (4 courses), and the **General Technical Electives** (4 courses). Students are

encouraged to work with their faculty adviser to create a plan tailored to fit their goals and interests. The department webpage provides several example programs for students interested in a variety of specific areas in computer science.

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 toward the major.

Prerequisite to the CS Major

ENGI E1006 Introduction to computing for engineers and applied scientists. All CS majors should take this course in their first or second semester.

Mathematics Requirements

Calculus Requirement: Take all three of the following:

1. MATH UN1101 (3)
2. MATH UN1102 (3)
3. APMA E2000 (4)

Linear Algebra Requirement: Select one of the following courses:

- COMS W3251 (4)
- MATH UN2010 (3)
- MATH UN2015 (3)
- MATH UN2020 (3)
- APMA E2101 (3)
- APMA E3101 (3)

Probability/Statistics Requirement: Select one of the following courses:

- IEOR E3658 (3)
- STAT UN1201 (3)
- STAT GU4001 (3)
- MATH UN2015 (3)

Note: Math UN2015 Linear Algebra and Probability may simultaneously satisfy both linear algebra and probability/statistics requirements without the need to take additional classes, thus reducing the total number of courses required.

Computer Science Core

Take all six of the following courses:

1. COMS W1004 or W1007 (3)
2. COMS W3134 (3) or W3137 (4)
3. COMS W3157 (4)
4. COMS W3203 (4)
5. COMS W3261 (3)
6. CSEE W3827 (3)

Area Foundation Courses

Select four from the following list:

- COMS W4111 (3)
- COMS W4113 (3)
- COMS W4115 (3)
- COMS W4118 (3)
- CSEE W4119 (3)
- COMS W4152 (3)
- COMS W4156 (3)
- COMS W4160 (3)
- COMS W4167 (3)
- COMS W4170 (3)
- COMS W4181 (3)
- CSOR W4231 (3)
- COMS W4236 (3)
- COMS W4701 (3)
- COMS W4705 (3)
- COMS W4731 (3)
- COMS W4733 (3)
- CBMF W4761 (3)
- COMS W4771 (3)
- CSEE W4824 (3)
- CSEE W4868 (3)

Computer Science Electives

Any four COMS courses, or jointly offered computer science courses such as CSXX or XXCS courses, that are worth at least 3 points and are at the 3000 level or above.

General Technical Electives

Four General Technical Elective (GTE) courses are required. GTE courses must be worth at least 3 points, at the 3000 level or above, and must be selected from the list of departments below. There are no exceptions.

- Any SEAS department
- Astronomy
- Biomedical Informatics
- Biological Science
- Chemistry
- Earth and Environmental Sciences
- Ecology, Evolution, and Environmental Biology
- Mathematics
- Physics
- Psychology
- Statistics
- Economics

Undergraduate Thesis

A student may, with adviser approval, choose to complete a thesis. A thesis may be used in place of up to 6 points from the Computer Science Electives requirement. A thesis may not be used in place of any Area Foundation Courses. A thesis consists of an independent theoretical or experimental investigation of an appropriate problem in computer science carried out under the supervision of a Computer Science Department faculty member. A formal written report is mandatory and an oral presentation may also be required.

Restrictions

Note: No more than 6 points of individual research, project, or thesis courses (including COMS W3902, W3998, W4901, W6901, and equivalent project/research courses from other departments) may be applied towards the computer science major. COMS W3999 Fieldwork cannot be used as a CS Elective. No more than one course from each set below may be applied towards the computer science major:

- IEOR E3658, STAT UN1201, STAT GU4001, MATH UN2015
- MATH UN2015, MATH UN2010, APAM E3101, COMS W3251
- COMS W4771, COMS W4721, STAT GU4241

Advanced Placement

Students who pass the Computer Science Advanced Placement (AP) Exam with a 4 or 5 will receive 3 points of credit and an exemption from COMS W1004.

GRADUATE PROGRAMS

The Department of Computer Science offers graduate programs leading to the degree of Master of Science and the degree of Doctor of Philosophy.

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

M.S. in Computer Science Program

The Master of Science (M.S.) program is intended for students with a bachelor's degree in Computer Science or a strongly related field who wish to broaden and deepen their understanding of computer science. Columbia University and the New York City environment provide excellent career opportunities with multiple industries. The program provides a unique opportunity to develop leading-edge in-depth knowledge of specific computer science disciplines.

Students in the M.S. program must complete a total of 30 points with a GPA of at least 2.7. Every student selects a track that focuses on a particular field of computer science. There are currently eight predefined M.S. tracks: Computational Biology; Computer Security; Foundations of Computer Science; Machine Learning; Natural Language Processing; Network Systems; Software Systems; Vision, Graphics, Interaction, and Robotics. Every track has a set of required courses and a wide range of elective courses that allow the students flexibility in designing their program according to their interests, under the guidance of a faculty adviser. Besides the eight predefined tracks, there is also the option of a M.S. Personalized track for students who want to study an area of computer science that is not covered by one of the eight tracks, and the option of the M.S. Thesis track for students who want to do extensive research in a subfield and write an M.S. thesis, under the supervision of a faculty member. Students in all the tracks are encouraged to pursue research if they wish, and many participate in research projects with the faculty. The faculty in the department conduct research in all areas of computer science. For detailed information on the M.S. program, please see cs.columbia.edu/education/ms.

Ph.D. in Computer Science Program

The primary focus of the doctoral program is research, with the philosophy that students learn best by doing—beginning as apprentices and becoming junior colleagues working with faculty on scholarly research projects. The faculty in the department conduct research in all areas of computer science. The degree of Doctor of Philosophy requires a dissertation based on the candidate's original research, which is supervised by a faculty member, and all students in the Ph.D. program are actively engaged in research throughout the program. Ph.D. students spend at least half of their time on research under the direction of their faculty adviser from their first day in the program and devote themselves full time to research after coursework and other preliminaries have been completed. Ph.D. students are also expected to participate in departmental and laboratory activities full time on campus throughout the program, except possibly for summer internships elsewhere, and the department does not consider admission of part-time Ph.D. students. Further information is available at cs.columbia.edu/education/phd.

DUAL DEGREE PROGRAM IN JOURNALISM AND COMPUTER SCIENCE

The Graduate School of Journalism and the School of Engineering and Applied Science offer a dual degree program leading to the M.S. degree in Journalism from the Graduate School of Journalism and the M.S. degree in Computer Science from the School of Engineering and Applied Science.

Admitted students enroll for a total of four semesters consisting of 27 points of Computer Science coursework in which an overall 2.7 GPA must be maintained and of 37 points of Journalism coursework. In addition to taking classes already offered at the two schools, students will take *Frontiers of computational journalism*, a course designed specifically for the dual program. The course will teach students about the impact of digital techniques on journalism; the emerging role of citizens in the news process; the influence of social media; and the changing business models that will support newsgathering. Students will use a hands-on approach to delve deeply into information design, focusing on how to build a site, section, or application from concept to development, ensuring the editorial goals are kept uppermost in mind

CS@CU MS BRIDGE PROGRAM IN COMPUTER SCIENCE

The CS@CU MS Bridge Program in Computer Science offers prospective applicants from noncomputer science backgrounds, including those without programming experience, the opportunity to acquire the knowledge and skills necessary to build careers in technology.

Admitted students will first take a total of seven undergraduate courses (the bridge curriculum) over two to three semesters, which will build the necessary foundation of programming and mathematical skills. There is flexibility for both scheduling and the choice of courses depending on a student's prior experience and concurrent obligations. Students will also be closely advised during this process in order to prepare for M.S. track selection. Once the bridge is completed with an overall 3.3 GPA or higher, students are then eligible for an automatic transfer into the M.S. in Computer Science program. Further information is available at cs.columbia.edu/ms-bridge.

COURSES IN COMPUTER SCIENCE

In the listing below, the designator COMS (Computer Science) is understood to precede all course numbers for which no designator is indicated. NOTE: Students may receive credit for only one of the following two courses: *COMS W1004 and W1005*. Likewise, students may receive credit for only one of the following three courses: *COMS W3134, W3136,* or *W3137*.

COMS W1001x or y Introduction to information science
3 pts. Lect: 3. Instructor to be announced.
Basic Introduction to concepts and skills in Information Sciences: human-computer interfaces, representing information digitally, organizing and searching information on the internet, principles of algorithmic problem solving, introduction to database concepts, introduction to programming in Python.

COMS W1002x Computing in context
4 pts. Lect: 4. *Professor Cannon.*
Introduction to elementary computing concepts and Python programming with domain-specific applications. Shared CS concepts and Python programming lectures with track-specific sections. Track themes will vary but may include computing for the social sciences, computing for economics and finance, digital humanities, and more. Intended for nonmajors. Students may receive

credit for only one of the following two courses: ENGI E1006 or COMS W1002.

COMS W1004x and y Introduction to computer science and programming in Java
3 pts. Lect: 3. Professor Cannon.
A general introduction to computer science for science and engineering students interested in majoring in computer science or engineering. Covers fundamental concepts of computer science, algorithmic problem-solving capabilities, and introductory Java programming skills. Assumes no prior programming background. Columbia University students may receive credit for only one of the following two courses: W1004 or W1005.

COMS W1005x or y Introduction to computer science and programming in MATLAB
3 pts. Lect: 3. Professor Blaer.
A general introduction to computer science concepts, algorithmic problem-solving capabilities, and programming skills in MATLAB. Assumes no prior programming background. Columbia University students may receive credit for only one of the following two courses: W1004 or W1005.

ENGI E1006x and y Introduction to computing for engineers and applied scientists
3 pts. Lect: 3. Professor Salleb-Aouissi.
An interdisciplinary course in computing intended for first year SEAS students. Introduces computational thinking, algorithmic problem solving and Python programming with applications in science and engineering. Assumes no prior programming background.

COMS W1007x Honors introduction to computer science
3 pts. Lect: 3. Professor Kender.
Prerequisite(s): AP Computer Science with a grade of 4 or 5 or similar experience. An honors-level introduction to computer science, intended primarily for students considering a major in computer science. Computer science as a science of abstraction. Creating models for reasoning about and solving problems. The basic elements of computers and computer programs. Implementing abstractions using data structures and algorithms. Taught in Java.

COMS W1404x and y Emerging scholars program seminar
1 pt. Sem: 1. Professor Cannon.
Corequisite(s): COMS W1004/1007 or ENGI E1006. Enrollment with instructor permission only. Peer-led weekly seminar intended for first- and second-year undergraduates considering a major in computer science. Pass/fail only.

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

COMS W3101x and y Programming languages
1 pt. Lect: 1. Members of the faculty.
Prerequisite(s): Fluency in at least one programming language. Introduction to a programming language. Each section is devoted to a specific language. Intended only for those who are already fluent in at least one programming language. Sections may meet for one hour per week for the whole term, for three hours per week for the first third of the term, or for two hours per week for the first six weeks. May be repeated for credit if different languages are involved.

COMS W3102x and y Development technologies
1–2 pts. Lect: 2. Lab: 0-2. Members of the faculty.
Prerequisite(s): Fluency in at least one programming language. Introduction to software development tools and environments. Each section is devoted to a specific tool or environment. One-point sections meet for two hours each week for half a semester, and two-point sections include an additional two-hour lab.

COMS W3107x Clean object-oriented design
3 pts. Lect: 3. Professor Kender.
Prerequisite(s): COMS W1004 or instructor's permission. May not take for credit if already received credit for COMS W1007. A course in designing, documenting, coding, and testing robust computer software, according to object-oriented design patterns and clean coding practices. Taught in Java. Object-oriented design principles include: use cases; CRC; UML; javadoc; patterns (adapter, builder, command, composite, decorator, facade, factory, iterator, lazy evaluation, observer, singleton, strategy, template, visitor); design by contract; loop invariants; interfaces and inheritance hierarchies; anonymous classes and null objects; graphical widgets; events and listeners; Java's Object class; generic types; reflection; timers, threads, and locks.

COMS W3132y Intermediate Computing in Python
4 pts. Lect: 4. Professors Janak and Cannon.
An intermediate interdisciplinary course in computing intended for non-CS majors, i.e., non-engineering (non-SEAS) and non-CS engineering students. Covers essential data structures and algorithms in Python, and practical software development skills. Teaches the application of computational thinking and algorithmic problem solving using the Python language in the student's field of study or area of interests. COMS W3132 is a follow-up course to COMS W1002 (Computing in Context) and ENGI E1006 (Introduction to Computing for Engineers and Applied Scientists) and assumes prior programming background at the level taught in those courses.

COMS W3134x and y Data structures in Java
3 pts. Lect: 3. Professor Blaer.
Prerequisite(s): COMS W1004 or knowledge of Java. Data types and structures: arrays, stacks, singly and doubly linked lists, queues, trees, sets, and graphs. Programming techniques for processing such structures: sorting and searching, hashing, garbage collection. Storage management. Rudiments of the analysis of algorithms. Taught in Java. Note: Due to significant overlap, students may receive credit for only one of the following three courses: COMS W3134, W3136, or W3137.

COMS W3136y Data structures with C/C++
4 pts. Lect: 3. Professor Lee.
Prerequisite(s): COMS W1004, W1005, W1007, or ENGI E1006. A second programming course intended for nonmajors with at least one semester of introductory programming experience. Basic elements of programming in C and C++, array-based data structures, heaps, linked lists, C programming in UNIX environment, object-oriented programming in C++, trees, graphs, generic programming, hash tables. Due to significant overlap, students may only receive credit for either COMS W3134, W3136, or W3137.

COMS W3137y Honors data structures and algorithms
4 pts. Lect: 3. Professor Blaer.
Prerequisite(s): COMS W1004 or W1007. Corequisite(s): COMS W3203. An honors introduction to data types and structures: arrays, stacks, singly and doubly linked lists, queues, trees, sets, and graphs. Programming techniques for processing such structures: sorting and searching, hashing, garbage collection. Storage management. Design and analysis of algorithms. Taught in Java. Note: Due to significant overlap, students may receive credit for only one of the following three courses: COMS W3134, W3136, or W3137.

COMS W3157x and y Advanced programming
4 pts. Lect: 4. Professor Lee.
Prerequisite(s): Two terms of programming experience. COMS W3134 or W3137. Recommended: Data Structures. C programming language and Unix systems programming. Also covers Git, Make, TCP/IP networking basics, C++ fundamentals.

COMS W3203x and y Discrete structures in mathematics and probability
4 pts. Lect: 3. Professor Salleb-Aouissi.
Prerequisite(s): MATH UN1102 or UN1201 or APMA E2000 and COMS W1002 or W1004 or W1007 or ENGI E1006. Logic and formal proofs, sets and relations, advanced proof techniques, number theory and modular arithmetic, graph theory, counting and basic probability, conditional probability and Bayes rule, random variables, expectation and variance, central limit theorem, probability distributions (Gaussians, binomial, and geometric).

COMS W3210x or y Scientific computation
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Two terms of calculus. Introduction to computation on digital computers. Design

and analysis of numerical algorithms. Numerical solution of equations, integration, recurrences, chaos, differential equations. Introduction to Monte Carlo methods. Properties of floating point arithmetic. Applications to weather prediction, computational finance, computational science, and computational engineering.

COMS W3251x and y Computational linear algebra
4 pts. Lect: 3. Professor Dear.
Prerequisite(s): MATH UN1102 or UN1201 or APMA E2000 and COMS W1002 or W1004 or W1007 or ENGI E1006. Functions and compositions. Vectors and linear functions, matrices and linear transforms, inverses and Gaussian elimination. Vector spaces, bases, subspaces, and dimension. Inner products, norms, and orthogonal projections. Eigenvectors and eigenvalues, spectral decomposition. Quadratic forms, and singular value decomposition. Note: Previously offered for 3 points.

COMS W3261x and y Computer science theory
3 pts. Lect: 3. Professor Malkin.
Prerequisite(s): COMS W3203. Corequisites: COMS W3134, W3136, or W3137. Regular languages: deterministic and nondeterministic finite automata, regular expressions. Context-free languages: context-free grammars, push-down automata. Turing machines, the Chomsky hierarchy, and the Church-Turing thesis. Introduction to complexity theory and NP-completeness.

COMS W3410y Computers and society
3 pts. Lect: 3. Professor Bellovin.
Broader impact of computers. Social networks and privacy. Employment, intellectual property, and the media. Science and engineering ethics. Suitable for nonmajors.

CSEE W3827x and y Fundamentals of computer systems
3 pts. Lect: 3. Professor Kim or Rubenstein.
Prerequisite(s): An introductory programming course. Fundamentals of computer organization and digital logic. Boolean algebra, Karnaugh maps, basic gates and components, flip-flops and latches, counters and state machines, basics of combinational and sequential digital design. Assembly language, instruction sets, ALUs, single-cycle and multi-cycle processor design, introduction to pipelined processors, caches, and virtual memory.

COMS E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Research training course. Recommended in preparation for laboratory-related research.

COMS W3902x and y Undergraduate thesis
1–6 pts. Members of the faculty.
Prerequisite(s): Agreement by faculty member to serve as thesis adviser. An independent theoretical or experimental investigation by an undergraduate major of an appropriate problem in computer science carried out under the supervision of a faculty member. A formal written report is mandatory and an oral presentation may also be required. May be taken over more than one term, in which case the grade is deferred until all 6 points have been completed. Consult the department for section assignment.

COMS W3995x or y Special topics in computer science
3 pts. Lect: 3.
Prerequisite(s): Instructor’s permission. Consult the department for section assignment. Special topics arranged as the need and availability arise. Topics are usually offered on a one-time basis. Since the content of this course changes each time it is offered, it may be repeated for credit.

COMS W3998x and y Undergraduate projects in computer science
1–3 pts. Members of the faculty.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. Independent project involving laboratory work, computer programming, analytical investigation, or engineering design. May be repeated for credit. Consult the department for section assignment.

COMS E3999x, y or s Fieldwork
1–2 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used toward the 128-credit degree requirement. Only for SEAS computer science undergraduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation may be required. May not be used as a technical or nontechnical elective. May not be taken for pass/fail credit or audited.

ECBM E4060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Cheng.
Introduction to computational biology with emphasis on genomic data science tools and methodologies for analyzing data, such as genomic sequences, gene expression measurements and the presence of mutations. Applications of machine learning and exploratory data analysis for predicting drug response and disease progression. Latest technologies related to genomic information, such as single-cell sequencing and CRISPR, and the contributions of genomic data science to the drug development process.

COMS W4111x and y Introduction to databases
3 pts. Lect: 3. Professor Gravano.
Prerequisite(s): COMS W3134, W3136, or W3137, or instructor’s permission. Covers definition of database systems, effective design of databases, querying databases, and developing applications using databases. Includes: entity-relationship modeling, logical design of relational databases, relational algebra, SQL, database security, and an overview of query optimization and transaction processing. Additional topics: NoSQL, graph, object-relational, cloud databases, data preparation, and cleaning of real-world data. Offers both programming and non-programming homework and projects, to accommodate different programming skills and backgrounds.

COMS W4112y Database system implementation
3 pts. Lect: 2.5. Professor Ross.
Prerequisite(s): COMS W4111; fluency in Java or C++. CSEE W3827 is recommended. The principles and practice of building large-scale database management systems. Storage methods and indexing, query processing and optimization, materialized views, transaction processing and recovery, object-relational databases, parallel and distributed databases, performance considerations. Programming projects are required.

COMS W4113x Fundamentals of large-scale distributed systems
3 pts. Lect: 3. Professor Geambasu.
Prerequisite(s): COMS W3134, W3136, or W3137. COMS W3157 or good working knowledge of C and C++. COMS W4118 or CSEE W4119. Design and implementation of large-scale distributed and cloud systems. Abstractions, design, and implementation techniques that enable the building of fast, scalable, fault-tolerant distributed systems. Topics include distributed communication models (e.g., sockets, remote procedure calls, distributed shared memory), distributed synchronization (clock synchronization, logical clocks, distributed mutex), distributed file systems, replication, consistency models, fault tolerance, distributed transactions, agreement and commitment, Paxos-based consensus, MapReduce infrastructures, scalable distributed databases. Combines concepts and algorithms with descriptions of real-world implementations at Google, Facebook, Yahoo, Microsoft, LinkedIn etc.

COMS W4115x and y Programming languages and translators
3 pts. Lect: 3. Professor Edwards or Ray.
Prerequisite(s): COMS W3134, W3136, or W3137 (or equivalent), W3261, and CSEE W3827, or instructor’s permission. Modern programming languages and compiler design. Imperative, object-oriented, declarative, functional, and scripting languages. Language syntax, control structures, data types, procedures and parameters, binding, scope, run-time organization, and exception handling. Implementation of language translation tools including compilers and interpreters. Lexical, syntactic, and semantic analysis; code generation; introduction to code optimization. Teams implement a language and its compiler.

COMS W4117x or y Compilers and interpreters
3 pts. Lect: 3.
Prerequisite(s): COMS W4115 or instructor’s permission. Continuation of COMS W4115, with broader and deeper investigation into the design and implementation of contemporary language translators, be they compilers or interpreters. Topics include parsing, semantic analysis, code generation and optimization, run-time environments, and compiler-compilers. A programming project is required.

COMS W4118x and y Operating systems, I
3 pts. Lect: 3. Professor Lee or Nieh.
Prerequisite(s): CSEE W3827 and knowledge of C and programming tools as covered in W3136, W3157, or W3101, or instructor's permission. Design and implementation of operating systems. Topics include process management, process synchronization and interprocess communication, memory management, virtual memory, interrupt handling, processor scheduling, device management, I/O, and file systems. Case study of the UNIX operating system. A programming project is required.

CSEE W4119x and y Computer networks
3 pts. Lect: 3. Professor Katz-Bassett.
Prerequisite(s): Comfort with basic probability and programming fluency in Python, C++, Java, or Ruby. Introduction to computer networks and the technical foundations of the internet, including applications, protocols, local area networks, algorithms for routing and congestion control, security, elementary performance evaluation. Several written and programming assignments required.

CSEE W4121y Computer systems for data science
3 pts. Lect: 3. Professor Cidon.
Prerequisite(s): Background in Computer System Organization and good working knowledge of C/C++. Corequisite(s): CSOR W4246, STAT GU4203, or equivalent approved by faculty adviser. Introduction to computer distributed systems with emphasis on warehouse scale computing systems. Topics include fundamental tradeoffs in computer systems, hardware and software techniques for exploiting instruction-level parallelism, data-level parallelism and task level parallelism, scheduling, caching, prefetching, network and memory architecture, latency and throughput optimizations, specializations, and introduction to programming data center computers.

COMS W4130x Principles and practice of parallel programming
3 pts. Lect: 2.5. Professor Kim.
Prerequisite(s): Experience in Java, basic understanding of analysis of algorithms. COMS W3134, W3136, or W3137 (or equivalent). Principles of parallel software design. Topics include task and data decomposition, load-balancing, reasoning about correctness, determinacy, safety, and deadlock-freedom. Application of techniques through semester-long design project implementing performant, parallel application in a modern parallel programming language.

COMS W4137y From algorithmic thinking to development
3 pts. Lect: 3. Professor Borowski.
Prerequisite(s): COMS W3134, COMS W3137, or COMS W3132. Algorithmic problem-solving and coding skills needed to devise solutions to interview questions for software engineering positions. Solutions are implemented in Python, Java, C, and C++. Approaches include brute-force, hashing, sorting, transform-and-conquer, greedy, and dynamic programming. Focus on experimentation and team work.

CSEE W4140x or y Networking laboratory
3 pts. Lect: 3. Professor Zussman.
Prerequisite(s): CSEE W4119 or equivalent. Students will learn how to put "principles into practice," in a hands-on networking lab course. The course will cover the technologies and protocols of the internet using equipment currently available to large internet service providers such as CISCO routers and end systems. A set of laboratory experiments provides hands-on experience with engineering wide-area networks and will familiarize students with the Internet Protocol (IP), Address Resolution Protocol (ARP), Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), the Domain Name System (DNS), routing protocols (RIP, OSPF, BGP), network management protocols (SNMP, and application-level protocols (FTP, TELNET, SMTP).

COMS W4152x Engineering software as a service
3 pts. Lect: 3. Professor Yang.
Prerequisite(s): COMS W3134, W3157, and CSEE W3827. Modern software engineering concepts and practices including topics such as Software-as-a-Service, Service-oriented Architecture, Agile Development, Behavior-driven Development, Ruby on Rails, and Dev/ops.

COMS W4153x Cloud computing
3 pts. Lect: 3. Professor Ferguson.
Prerequisite(s): COMS W4111. Software engineering skills necessary for developing cloud computing and software-as-a-service applications, covering topics such as service-oriented architectures, message-driven applications, and platform integration. Includes theoretical study, practical application, and collaborative project work.

COMS W4156x Advanced software engineering
3 pts. Lect: 3. Professor Kaiser.
Prerequisite(s): COMS W3157 or equivalent. Software lifecycle using frameworks, libraries, and services. Major emphasis on software testing. Centers on a team project.

COMS W4160y Computer graphics
3 pts. Lect: 3. Professor Reed.
Prerequisite(s): COMS W3134, W3136, or W3137; W4156 is recommended. Strong programming background and some mathematical familiarity including linear algebra is required. Introduction to computer graphics. Topics include 3D viewing and projections, geometric modeling using spline curves, graphics systems such as OpenGL, lighting and shading, and global illumination. Significant implementation is required: the final project involves writing an interactive 3D video game in OpenGL.

COMS W4162x or y Advanced computer graphics
3 pts. Lect: 3. Professor Zheng.
Prerequisite(s): COMS W4160 or equivalent, or instructor's permission. A second course in computer graphics covering more advanced topics including image and signal processing, geometric modeling with meshes, advanced image synthesis including ray tracing and global illumination, and other topics as time permits. Emphasis will be placed both on implementation of systems and important mathematical and geometric concepts such as Fourier analysis, mesh algorithms and subdivision, and Monte Carlo sampling for rendering. Note: Course will be taught every two years.

COMS W4167x or y Computer animation
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Multivariable calculus, linear algebra, C++ programming proficiency. COMS W4156 recommended. Theory and practice of physics-based animation algorithms, including animated clothing, hair, smoke, water, collisions, impact, and kitchen sinks. Topics covered: integration of ordinary differential equations, formulation of physical models, treatment of discontinuities including collisions/contact, animation control, constrained Lagrangian Mechanics, friction/dissipation, continuum mechanics, finite elements, rigid bodies, thin shells, discretization of Navier-Stokes equations. General education requirement: quantitative and deductive reasoning (QUA).

COMS W4170x or y User interface design
3 pts. Lect: 3. Professor Chilton or Feiner.
Prerequisite(s): COMS W3134, W3136, or W3137. Introduction to the theory and practice of computer user interface design, emphasizing the software design of graphical user interfaces. Topics include basic interaction devices and techniques, human factors, interaction styles, dialogue design, and software infrastructure. Design and programming projects are required.

COMS W4172y 3D user interfaces and augmented reality
3 pts. Lect: 3. Professor Feiner.
Prerequisite(s): COMS W4160 or W4170 or instructor's permission. Design, development, and evaluation of 3D user interfaces. Interaction techniques and metaphors, from desktop to immersive. Selection and manipulation. Travel and navigation. Symbolic, menu, gestural, and multimodal interaction. Dialogue design. 3D software support. 3D interaction devices and displays. Virtual and augmented reality. Tangible user interfaces. Review of relevant 3D math.

COMS W4181x Security I
3 pts. Lect: 3. Professor Jana.
Prerequisite(s): COMS W3157 or equivalent. Introduction to security. Threat models. Operating system security features. Vulnerabilities and tools. Firewalls, virtual private networks, viruses. Mobile and app security. Usable security.
Note: May not earn credit for both W4181 and W4180 or W4187.

COMS W4182y Security II
3 pts. Lect: 3. Professor Bellovin.
Prerequisite(s): COMS W4181, COMS W4118, CSEE W4119. Advanced security. Centralized, distributed, and cloud system security. Cryptographic protocol design choices. Hardware

and software security techniques. Security testing and fuzzing. Blockchain. Human security issues. Note: May not earn credit for both W4182 and W4180 or W4187.

COMS W4186x Malware analysis and reverse engineering
3 pts. Lect: 3. Lab 3. Professor Sikorski.
Prerequisite(s): COMS W3157 or equivalent; CSEE W3827. Hands-on analysis of malware. How hackers package and hide malware and viruses to evade analysis. Disassemblers, debuggers, and other tools for reverse engineering. Deep study of Windows Internals and x86 assembly.

ORCS E4200y Data-driven decision modeling
3 pts. Lect: 3. Professor Dear or Zhang.
Introduction to modeling, estimating, and solving decision-making problems in the context of artificial intelligence and analytics. Potential topics include choice models, quantity models, online learning using multi-armed bandits, dynamic decision modeling, dynamic games, and Bayesian learning theory. Practice both theory and applications using Python programming.

COMS W4203y Graph theory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): COMS W3203. General introduction to graph theory. Isomorphism testing, algebraic specification, symmetries, spanning trees, traversability, planarity, drawings on higher-order surfaces, colorings, extremal graphs, random graphs, graphical measurement, directed graphs, Burnside-Polya counting, voltage graph theory.

COMS W4223y Networks, Crowds and the Web
3 pts. Lect: 3. Professor Chaintreau.
Prerequisite(s): Familiarity with elementary concepts of probability (any class that includes probability suffices), and taken one class of data structures or has experience programming with data. Introduces fundamental ideas and algorithms on networks of information collected by online services. Covers properties pervasive in large networks, dynamics of individuals that lead to large collective phenomena, mechanisms underlying the web economy, and results and tools informing societal impact of algorithms on privacy, polarization and discrimination.

CSOR W4231x Analysis of algorithms I
3 pts. Lect: 3. Professor Yannakakis, Drinea, or Andoni.
Prerequisite(s): COMS W3134, W3136 or W3137, and W3203. Introduction to the design and analysis of efficient algorithms. Topics include models of computation, efficient sorting and searching, algorithms for algebraic problems, graph algorithms, dynamic programming, probabilistic methods, approximation algorithms, and NP-completeness.

COMS W4232y Advanced algorithms
3 pts. Lect: 3. Professor Andoni.
Prerequisite(s): COMS W4231. Introduces classic and modern algorithmic ideas central to many areas of Computer Science. Focus on most powerful paradigms and techniques of how to design and measure efficiency of algorithms. Broad intent, covering diverse algorithmic techniques. Covered topics are implemented and used in industry. Topics include: hashing, sketching/streaming, nearest neighbor search, graph algorithms, spectral graph theory, linear programming, models for large-scale computation, and other related topics.

COMS W4236y Introduction to computational complexity
3 pts. Lect: 3. Professor Chen.
Prerequisite(s): COMS W3261. Develops a quantitative theory of the computational difficulty of problems in terms of the resources (e.g., time, space) needed to solve them. Classification of problems into complexity classes, reductions and completeness. Power and limitations of different modes of computation such as nondeterminism, randomization, interaction and parallelism.

COMS W4241y Numerical algorithms and complexity
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Knowledge of a programming language. Some knowledge of scientific computation is desirable. Modern theory and practice of computation on digital computers. Introduction to concepts of computational complexity. Design and analysis of numerical algorithms. Applications to computational finance, computational science, and computational engineering.

STCS W4242x or y Introduction to data science
3 pts. Lect: 3. Professor Salleb-Aouissi.
Practical techniques for working with large-scale data. Topics include statistical modeling and machine learning, data pipelines, programming languages, “big data” tools, and real-world topics and case studies. Statistical and data manipulation software required. Intended for nonquantitative graduate-level disciplines.

COMS W4252x or y Introduction to computational learning theory
3 pts. Lect: 3. Professor Servedio.
Prerequisite(s): CSOR W4231 or COMS W4236 or W3203 and instructor’s permission or COMS W3261 and instructor’s permission. Possibilities and limitations of performing learning by computational agents. Topics include computational models of learning, polynomial time learnability, learning from examples and learning from queries to oracles. Computational and statistical limitations of learning. Applications to Boolean functions, geometric functions, automata.

COMS W4261x or y Introduction to cryptography
3 pts. Lect: 2.5. Professor Malkin.
Prerequisite(s): Comfort with basic discrete math and probability. Recommended: COMS W3261 or CSOR W4231. An introduction to modern cryptography, focusing on the complexity-theoretic foundations of secure computation and communication in adversarial environments; a rigorous approach, based on precise definitions and provably secure protocols. Topics include private and public key encryption schemes, digital signatures, authentication, pseudorandom generators and functions, one-way functions, trapdoor functions, number theory and computational hardness, identification and zero knowledge protocols.

COMS W4281x or y Introduction to quantum computing
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Knowledge of linear algebra. Prior knowledge of quantum mechanics is not required although helpful. Introduction to quantum computing. Shor’s factoring algorithm, Grover’s database search algorithm, the quantum summation algorithm. Relationship between classical and quantum computing. Potential power of quantum computers.

EECS E4340x Computer hardware design
3 pts. Lect: 2. Lab: 3. Professor Sethumadhavan.
Prerequisite(s): ELEN E3331 and CSEE W3827. Practical aspects of computer hardware design through the implementation, simulation, and prototyping of a PDP-8 processor. High-level and assembly languages, I/O, interrupts, datapath and control design, pipelining, busses, memory architecture. Programmable logic and hardware prototyping with FPGAs. Fundamentals of VHDL for register-transfer level design. Testing and validation of hardware. Hands-on use of industry CAD tools for simulation and synthesis.

COMS W4419x or y Internet, technology, economics, and policy
3 pts. Lect: 3. Professor Schulzrinne.
Technology, economics, and policy aspects of the internet. Summarizes how the internet works technically, including protocols, standards, radio spectrum, global infrastructure and interconnection. Micro-economics with a focus on media and telecommunication economic concerns, including competition and monopolies, platforms, and behavioral economics. U.S. constitution, freedom of speech, administrative procedures act and regulatory process, universal service, role of FFC. Not a substitute for CSEE W4119. Suitable for nonmajors. May not be used as a track elective for computer science major.

COMS W4444x Programming and problem solving
3 pts. Lect: 3. Professor Ross.
Prerequisite(s): COMS W3134, W3136, or W3137, and CSEE W3827. Hands-on introduction to solving open-ended computational problems. Emphasis on creativity, cooperation, and collaboration. Projects spanning a variety of areas within computer science, typically requiring the development of computer programs. Generalization of solutions to broader problems, and specialization of complex problems to make them manageable. Team-oriented projects, student presentations, and in-class participation required.

COMS W4460y Principles of innovation and entrepreneurship
3 pts. Lect: 3.
Prerequisite(s): COMS W3134, W3136, or W3137 (or equivalent), or instructor’s permission. Team

project-centered course focused on principles of planning, creating, and growing a technology venture. Topics include identifying and analyzing opportunities created by technology paradigm shifts, designing innovative products, protecting intellectual property, engineering innovative business models.

MECS E4510x Evolutionary computation and design automation
3 pts. Lect: 3. Professor Lipson.
Prerequisite(s): Basic programming experience in any language. Fundamental and advanced topics in evolutionary algorithms and their application to open-ended optimization and computational design. Covers genetic algorithms, genetic programming, and evolutionary strategies, as well as governing dynamic of coevolution and symbiosis. Includes discussions of problem representations and applications to design problems in a variety of domains including software, electronics, and mechanics.

ORCS E4529y Reinforcement learning
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): Probability and statistics, basic optimization (e.g., familiarity with linear and convex optimization, gradient descent, basic algorithm design constructs), familiarity with programming in Python. Markov Decision Processes (MDP) and Reinforcement Learning (RL) problems. Reinforcement Learning algorithms including Q-learning, policy gradient methods, actor-critic method. Reinforcement learning while doing exploration-exploitation dilemma, multi-armed bandit problem. Monte Carlo Tree Search methods; Distributional, Multi-agent, and Causal Reinforcement Learning.

COMS W4560x Introduction to computer applications in healthcare and biomedicine
3 pts. Lect: 3.
Prerequisite(s): Experience with computers and a passing familiarity with medicine and biology. Undergraduates in their senior or junior years may take this course only if they have adequate background in mathematics and receive permission from the instructor. An overview of the field of biomedical informatics, combining perspectives from medicine, computer science, and social science. Use of computers and information in healthcare and the biomedical sciences, covering specific applications and general methods, current issues, capabilities and limitations of biomedical informatics. Biomedical Informatics studies the organization of medical information, the effective management of information using computer technology, and the impact of such technology on medical research, education, and patient care. The field explores techniques for assessing current information practices, determining the information needs of healthcare providers and patients, developing interventions using computer technology, and evaluating the impact of those interventions.

MECS E4603x Applied robotics: algorithms and software
3 pts. Lect: 3. Professor Ciocarlie.
Prerequisite(s): Fundamental programming skills (e.g., COMS W1002, W1004, W1005, ENGI E1006, or equivalent). Science and systems aspects of Robotics from applied perspective, focusing on algorithms and software tools. Spatial reasoning; tools for manipulating and visualizing spatial relationships. Analysis of robotic manipulators; numerical methods for kinematic analysis. Motion planning, search-based and stochastic approaches. Applications for force and impedance control. Grading based on combination of exams and projects implemented using Robot Operating System (ROS) software framework and executed on real and simulated robotic manipulators.

COMS W4701x or y Artificial intelligence
3 pts. Lect: 3. Professor Salleb-Aouissi or Dear.
Prerequisite(s): COMS W3134, W3136, or W3137 and any course on probability. Recommended: Prior knowledge of Python. Overview of Artificial Intelligence (AI) covering Search, Problem Solving, Game Playing, Knowledge Representation, Propositional logic, Predicate Calculus (first order logic), Reasoning under uncertainty, Machine Learning, and other topics in AI (including vision, natural language processing, and robotics) as time permits.

COMS W4705x Natural language processing
3 pts. Lect: 3. Professor McKeown.
Prerequisite(s): COMS W3134, W3136, or W3137 (or equivalent), or instructor's permission. Computational approaches to natural language generation and understanding. Recommended preparation: Some previous or concurrent exposure to AI or machine learning. Topics include information extraction, summarization, machine translation, dialogue systems, and emotional speech. Particular attention is given to robust techniques that can handle understanding and generation for the large amounts of text on the web or in other large corpora. Programming exercises in several of these areas.

COMS W4706y Spoken language processing
3 pts. Lect: 3. Professor Hirschberg.
Prerequisite(s): COMS W3134, W3136, or W3137 (or equivalent), or instructor's permission. Computational approaches to speech generation and understanding. Topics include speech recognition and understanding, speech analysis for computational linguistics research, and speech synthesis. Speech applications including dialogue systems, data mining, summarization, and translation. Exercises involve data analysis and building a small text-to-speech system.

COMS W4725x or y Knowledge representation and reasoning
3 pts. Lect: 3.
Prerequisite(s): COMS W4701. General aspects of knowledge representation (KR). The two fundamental paradigms (semantic networks and frames) and illustrative systems. Topics include hybrid systems, time, action/plans, defaults, abduction, and case-based reasoning. Throughout the course particular attention is paid to design trade-offs between language expressiveness and reasoning complexity, and issues relating to the use of KR systems in larger applications.

COMS W4731x or y Computer vision I: first principles
3 pts. Lect: 3. Professor Nayar.
Prerequisite(s): Fundamentals of calculus, linear algebra, and C programming. Students without any of these prerequisites are advised to contact the instructor prior to taking the course. Introductory course in computer vision. Topics include image formation and optics, image sensing, binary images, image processing and filtering, edge extraction and boundary detection, region growing and segmentation, pattern classification methods, brightness and reflectance, shape from shading and photometric stereo, texture, binocular stereo, optical flow and motion, 2D and 3D object representation, object recognition, vision systems and applications.

COMS W4732y Computer vision II: learning
3 pts. Lect: 3. Professor Vondrick.
Prerequisite(s): COMS E4731. Fundamentals of calculus, linear algebra, and C programming. Students without any of these prerequisites are advised to contact the instructor prior to taking the course. Advanced course in computer vision. Topics include convolutional networks and back-propagation, object and action recognition, self-supervised and few-shot learning, image synthesis and generative models, object tracking, vision and language, vision and audio, 3D representation, interpretability, and bias, ethics, and media deception.

COMS W4733x or y Computational aspects of robotics
3 pts. Lect: 3. Professors Dear or Song.
Prerequisite(s): COMS3134W or COMS3136W or COMS3137W and COMS3251W or MATH2010UN or APMA2101E or APMA3101E or MATH2015UN and STAT4001GU or IEOR3658E or STAT1201UN or MATH2015UN. Proficiency in Python or a similar programming language. Introduction to fundamental problems and algorithms in robotics. Topics include configuration spaces, motions and sensor models, search and sampling-based planning, state estimation, localization and mapping, perception, and learning.

COMS W4735x or y Visual interfaces to computers
3 pts. Lect: 3. Professor Kender.
Prerequisite(s): COMS W3134, W3136, or W3137. Visual input as data and for control of computer systems. Survey and analysis of architecture, algorithms, and underlying assumptions of commercial and research systems that recognize and interpret human gestures, analyze imagery such as fingerprint or iris patterns, generate natural language descriptions of medical or map imagery. Explores foundations in human psychophysics, cognitive science, and artificial intelligence.

COMS W4737x or y Biometrics
3 pts. Lect: 3. Professor Belhumeur.
Prerequisite(s): A background at the sophomore level in computer science, engineering, or like discipline. We will explore the latest advances in biometrics as well as the machine learning techniques behind them. Students will learn

how these technologies work and how they are sometimes defeated. Grading will be based on homework assignments and a final project. There will be no midterm or final exam. Shares lectures with COMS E6737. Students taking COMS E6737 are required to complete additional homework problems and undertake a more rigorous final project. Students will only be allowed to earn credit for COMS W4737 or COMS E6737 but not both.

EECS E4750x or y Heterogeneous computing for signal and data processing
3 pts. Lect: 2. Professor Marianetti.
Prerequisite(s): ELEN E3801 and COMS W3134 or similar, recommended. Methods for deploying signal and data processing algorithms on contemporary general purpose graphics processing units (GPGPUs) and heterogeneous computing infrastructures. Using programming languages such as OpenCL and CUDA for computational speedup in audio, image, and video processing and computational data analysis. Significant design project.

CBMF W4761x or y Computational genomics
3 pts. Lect: 3. Professor Pe'er.
Prerequisite(s): Introductory probability and statistics and basic programming skills. Provides comprehensive introduction to computational techniques for analyzing genomic data including DNA, RNA and protein structures; microarrays; transcription and regulation; regulatory, metabolic and protein interaction networks. The course covers sequence analysis algorithms, dynamic programming, hidden Markov models, phylogenetic analysis, Bayesian network techniques, neural networks, clustering algorithms, support vector machines, Boolean models of regulatory networks, flux based analysis of metabolic networks and scale-free network models. The course provides self-contained introduction to relevant biological mechanisms and methods.

COMS W4762x Machine learning for functional genomics
3 pts. Lect: 3. Professor Knowles.
Prerequisite(s): Proficiency in a high-level programming language (Python/R/Julia). Recommended: introductory machine learning class (such as COMS W4771). Introduces modern probabilistic machine learning methods using applications in data analysis tasks from functional genomics, where massively-parallel sequencing is used to measure the state of cells, e.g., what genes are being expressed, what regions of DNA ("chromatin") are active ("open") or bound by specific proteins.

COMS W4771y Machine learning
3 pts. Lect: 3. Professor Hsu or Verma.
Prerequisite(s): Any introductory course in linear algebra and any introductory course in statistics are both required. Highly recommended: COMS W4701 or knowledge of artificial intelligence. Topics from generative and discriminative machine learning including least squares methods, support vector machines, kernel methods, neural networks, Gaussian distributions, linear classification, linear regression, maximum likelihood, exponential family distributions, Bayesian networks, Bayesian inference, mixture models, the EM algorithm, graphical models and hidden Markov models. Algorithms implemented in MATLAB.

COMS W4772x Advanced machine learning
3 pts. Lect: 3. Professor Hsu.
Prerequisite(s): COMS W4771 or instructor's permission; knowledge of linear algebra and introductory probability or statistics is required. An exploration of advanced machine learning tools for perception and behavior learning. How can machines perceive, learn from, and classify human activity computationally? Topics include appearance-based models, principal and independent components analysis, dimensionality reduction, kernel methods, manifold learning, latent models, regression, classification, Bayesian methods, maximum entropy methods, real-time tracking, extended Kalman filters, time series prediction, hidden Markov models, factorial HMMs, input-output HMMs, Markov random fields, variational methods, dynamic Bayesian networks, and Gaussian/Dirichlet processes. Links to cognitive science.

COMS W4773y Machine learning theory
3 pts. Lect: 3. Professor Hsu.
Prerequisite(s): COMS W4771. Theoretical study of algorithms for machine learning and high-dimensional data analysis. Topics include high-dimensional probability, theory of generalization and statistical learning, online learning and optimization, spectral analysis.

COMS W4774y Unsupervised learning
3 pts. Lect: 3. Professor Verma.
Prerequisite(s): COMS W4771 and background in probability and statistics, linear algebra, and multivariate calculus. Ability to program in a high-level language, and familiarity with basic algorithm design and coding principles. Core topics from unsupervised learning such as clustering, dimensionality reduction and density estimation. Topics in clustering: k-means clustering, hierarchical clustering, spectral clustering, clustering with various forms of feedback, good initialization techniques and convergence analysis of various clustering procedures. Topics in dimensionality reductions: linear techniques such as PCA, ICA, Factor Analysis, Random Projections, non-linear techniques such as LLE, ISOMap, Laplacian Eigenmaps, tSNE, and study of embeddings of general metric spaces, what sorts of theoretical guarantees can one provide about such techniques. Miscellaneous topics: design and analysis of data structures for fast Nearest Neighbor search such as Cover Trees and LSH. Algorithms will be implemented in either Matlab or Python.

COMS W4775y Causal inference
3 pts. Lect: 3. Professor Bareinboim.
Prerequisite(s): Discrete Math, Calculus, Statistics (basic probability, modeling, experimental design), some programming experience. Causal Inference theory and applications. Theoretical topics include 3-layer causal hierarchy, causal bayesian networks, structural learning, identification problem and do-calculus, linear identifiability, bounding, and counterfactual analysis. Applied topics include intersection with statistics, empirical-data sciences (social and health), and AI and ML.

COMS W4776x Machine learning for data science
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): IEOR E4150 or STAT GU4001 or equivalent, COMS W3251 or equivalent. Introduction to machine learning, emphasis on data science. Topics include least square methods, Gaussian distributions, linear classification, linear regression, maximum likelihood, exponential family distributions, Bayesian networks, Bayesian inference, mixture models, the EM algorithm, graphical models, hidden Markov models, support vector machines kernel methods. Emphasizes methods and problems relevant to big data. Students may not receive credit for both COMS W4771 and W4776.

CSEE W4823x or y Advanced logic design
3 pts. Lect: 3. Professor Nowick.
Prerequisite(s): CSEE W3827, or a half-semester introduction to digital logic, or equivalent. An introduction to modern digital system design. Advanced topics in digital logic: controller synthesis (Mealy and Moore machines); adders and multipliers; structured logic blocks (PLDs, PALs, ROMs); iterative circuits. Modern design methodology: register transfer level modeling (RTL); algorithmic state machines (ASMs); introduction to hardware description languages (VHDL or Verilog); system-level modeling and simulation; design examples.

CSEE W4824x Computer architecture
3 pts. Lect: 3. Professor Sethumadhavan.
Prerequisite(s): CSEE W3827 or equivalent. Focuses on advanced topics in computer architecture, illustrated by case studies from classic and modern processors. Fundamentals of quantitative analysis. Pipelining. Memory hierarchy design. Instruction-level and thread-level parallelism. Data-level parallelism and graphics processing units. Multiprocessors. Cache coherence. Interconnection networks. Multi-core processors and systems-on-chip. Platform architectures for embedded, mobile, and cloud computing.

CSEE W4840y Embedded systems
3 pts. Lect: 3. Professor Edwards.
Prerequisite(s): CSEE W4823. Embedded system design and implementation combining hardware and software. I/O, interfacing, and peripherals. Weekly laboratory sessions and term project on design of a microprocessor-based embedded system including at least one custom peripheral. Knowledge of C programming and digital logic required. Lab required.

CSEE E4868x or y System-on-chip platforms
3 pts. Lect: 3. Professor Carloni.
Prerequisite(s): COMS W3157 and CSEE W3827 Design and programming of System-on-Chip (SoC) platforms. Topics include overview of technology and economic trends, methodologies

and supporting CAD tools for system-level design; models of computation, the SystemC language, transaction-level modeling, hardware-software partitioning, high-level synthesis, system programming, on-chip communication, memory organization, power management and optimization, integration of programmable processor cores and specialized accelerators. Case studies of modern SoC platforms for various classes of applications.

COMS E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

COMS W4901x and y Projects in computer science
1–3 pts. Members of the faculty.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. A second-level independent project involving laboratory work, computer programming, analytical investigation, or engineering design. May be repeated for credit. Consult the department for section assignment.

COMS W4995x or y Special topics in computer science, I
3 pts. Lect: 3. Members of the faculty.
Selected topics in computer science. Content and prerequisites vary between sections and semesters. May be repeated for credit. Check "topics course" webpage on the department website for more information on each section.

COMS W4996x or y Special topics in computer science, II
3 pts. Lect: 3.
Prerequisite(s): Instructor's permission. A continuation of COMS W4995 when the special topic extends over two terms.

COMS E6111y Advanced database systems
3 pts. Lect: 2. Professor Gravano.
Prerequisite(s): COMS W4111 and knowledge of Java or instructor's permission. Continuation of COMS W4111, covers latest trends in both database research and industry: information retrieval, web search, data mining, data warehousing, OLAP, decision support, multimedia databases, and XML and databases. Programming projects required.

COMS E6113y Topics In database systems
3 pts. Lect: 2.
Prerequisite(s): COMS W4111. Concentration on some database paradigm, such as deductive, heterogeneous, or object-oriented, and/or some database issue, such as data modeling, distribution, query processing, semantics, or transaction management. A substantial project is typically required. May be repeated for credit with instructor's permission.

COMS E6114y Advanced distributed systems
3 pts. Lect: 2. Professor Geambasu.
Prerequisite(s): COMS W4113 and W4118. Reviews influential research that provides the basis of most large-scale, cloud infrastructures today. Students read, present, and discuss papers. Topics include distributed consensus, consistency models and algorithms, service-oriented architectures, large-scale data storage, distributed transactions, big-data processing frameworks, distributed systems security. Reviews established results and state-of-the-art research.

COMS E6117x or y Topics in programming languages and translators
3 pts. Lect: 2.
Prerequisite(s): COMS W4115 or instructor's permission. Concentration on the design and implementation of programming languages, and tools focused on advanced applications in new areas in software verification, distributed systems, programming in the large, and web computing. A substantial project is typically required. May be repeated for credit.

COMS E6118y Operating systems, II
3 pts. Lect: 2. Professor Nieh.
Prerequisite(s): COMS W4118. Corequisite(s): CSEE W4119. Continuation of COMS W4118, with emphasis on distributed operating systems. Topics include interfaces to network protocols, distributed run-time binding, advanced virtual memory issues, advanced means of interprocess communication, file system design, design for extensibility, security in a distributed environment. Investigation is deeper and more hands-on than in COMS W4118. A programming project is required.

COMS E6121x Reliable software
3 pts. Lect: 3. Professor Yang.
Prerequisite(s): at least one of COMS W4118, W4115, or W4117, or significant software development experiences. Topics include automated debugging, automated software repair, concurrent software reliability, software error detection, and more.

COMS E6123x or y Programming environments and software tools (PEST)
3 pts. Lect: 2. Professor Kaiser.
Prerequisite(s): COMS W4156 or equivalent. Software methodologies and technologies concerned with development and operation of today's software systems. Reliability, security, systems management and societal issues. Emerging software architectures such as enterprise and grid computing. Term paper and programming project. Seminar focus changes frequently to remain timely.

COMS E6124x Hardware security
3 pts. Lect: 3. Professor Sethumadhavan.
Prerequisite(s): CSEE W3827 and COMS W3157. Recommended: CSEE W4824 and COMS W4187. Techniques for securing the foundational aspects of all computing devices and systems. Topics include: hardware-up security, hardware supply chain trust and security, storing secrets in hardware, boot time trust and security, side channel attacks and defenses, hardware support for compartmentalization, fault attacks and defenses, hardware support to strengthen software: memory safety, control flow integrity, information flow tracking, diversity, obfuscation, anomaly detection. Hardware support for accelerating cryptography and applied cryptography.

COMS E6125y Web-enhanced information management (WHIM)
3 pts. Lect: 2. Professor Kaiser.
Prerequisite(s): At least one COMS W41xx or COMS E61xx course and/or COMS W4444, or instructor's permission. Strongly recommended: COMS W4111. History of hypertext, markup languages, groupware and the web. Evolving web protocols, formats and computation paradigms such as HTTP, XML and Web Services. Novel application domains enabled by the web and societal issues. Term paper and programming project. Seminar focus changes frequently to remain timely.

COMS E6156y Topics in software engineering
3 pts. Lect: 2. Professor Kaiser.
Topics in software engineering arranged as the need and availability arises, usually offered on a one-time basis. Since the content of this course changes, it may be repeated for credit with instructor approval. Consult the department for section assignment. Software methodologies and technologies concerned with development and operation of today's software systems. Reliability, security, privacy, sustainability, and societal issues. Emerging software architectures such as microservices, serverless, and deep learning. Term paper and programming project.

COMS E6160x or y Topics in computer graphics
3 pts. Lect: 2. Professor Belhumeur.
Prerequisite(s): COMS W4160 or instructor's permission. An advanced graduate course, involving study of an advanced research topic in Computer Graphics. Content varies between offerings, and the course may be repeated for credit. Recent offerings have included appearance models in graphics, and high quality real-time rendering.

COMS E6173x Virtual reality and augmented reality
3 pts. Lect: 2. Professor Feiner.
Prerequisite(s): Recommended COMS W4172 (3D User Interfaces and Augmented Reality) or equivalent and familiarity with developing in Unity or instructor's permission. This course will cover selected topics in virtual reality (VR) and augmented reality (AR). There are two main components, with everyone participating in both: papers and projects.

COMS E6174y Interaction design: a perceptual approach
3 pts. Lect: 3.
Prerequisite(s): COMS W4170 or instructor's permission. Design methodology for special-purpose user interfaces. Emphasis on how psychology and perception inform good design. Interviewing and task modeling, participatory design, and low-fidelity prototyping. Applications of brain research, graphic design and art to develop custom user interfaces components, screen layouts, and interaction techniques for application-specific systems.

COMS E6176x or y User interfaces for mobile and wearable computing
3 pts. Lect: 2. Professor Feiner.
Prerequisite(s): COMS W4170 or instructor’s permission. Introduction to research on user interfaces for mobile and wearable computing through lectures, invited talks, student-led discussions of important papers, and programming projects. Designing and authoring for mobility and wearability. Ubiquitous/pervasive computing. Collaboration with other users. Display, interaction, and communication technologies. Sensors for tracking position, orientation, motion, environmental context, and personal context. Applications and social consequences.

COMS E6178y Human–computer interaction seminar
3 pts. Lect: 2.5. Professor Smith.
Prerequisite(s): COMS W4170. Human–computer interaction (HCI) studies (1) what computers are used for, (2) how people interact with computers, and (3) how either of those should change in the future. Topics include ubiquitous computing, mobile health, interaction techniques, social computing, mixed reality, accessibility, and ethics. Activities include readings, presentations, and discussions of research papers. Substantial HCI research project required.

CSEE E6180x or y Modeling and performance
3 pts. Lect: 2. Professor Misra.
Prerequisite(s): COMS W4118 and STAT GU4001. Introduction to queuing analysis and simulation techniques. Evaluation of time-sharing and multiprocessor systems. Topics include priority queuing, buffer storage, and disk access, interference and bus contention problems, and modeling of program behaviors.

COMS E6181x or y Advanced internet services
3 pts. Lect: 2. Professor Schulzrinne.
In-depth survey of protocols and algorithms needed to transport multimedia information across the internet, including audio and video encoding, multicast, quality-of-service, voice-over IP, streaming media and peer-to-peer multimedia systems. Includes a semester-long programming project.

COMS E6183x or y Advanced topics in network security
3 pts. Lect: 3. Professor Jana.
Prerequisite(s): COMS W4180, CSEE W4119 and COMS W4261 recommended. Review the fundamental aspects of security, including authentication, authorization, access control, confidentiality, privacy, integrity, and availability. Review security techniques and tools, and their applications in various problem areas. Study the state of the art in research. A programming project is required.

COMS E6184y Seminar on anonymity and privacy
3 pts. Lect: 3.
Prerequisite(s): COMS W4261 or W4180 or CSEE W4119 or instructor’s permission. Covers the following topics: Legal and social framework for privacy. Data mining and databases. Anonymous commerce and internet usage. Traffic analysis. Policy and national security considerations. Classes are seminars with students presenting papers and discussing them. Seminar focus changes frequently to remain timely.

COMS E6185x or y Intrusion and anomaly detection systems
3 pts. Lect: 2. Professor Stolfo.
Pre- or corequisite: COMS W4180 Network security. The state of threats against computers, and networked systems. An overview of computer security solutions and why they fail. Provides a detailed treatment for network and host-based intrusion detection and intrusion prevention systems. Considerable depth is provided on anomaly detection systems to detect new attacks. Covers issues and problems in e-mail (spam, and viruses) and insider attacks (masquerading and impersonation).

COMS E6232x or y Analysis of algorithms, II
3 pts. Lect: 2.
Prerequisite(s): CSOR W4231. Continuation of CSOR W4231.

COMS E6253y Advanced topics in computational learning theory
3 pts. Lect: 3. Professor Servedio.
Prerequisite(s): CSOR W4231 or equivalent; COMS W4252 or W4236 helpful but not required. In-depth study of inherent abilities and limitations of computationally efficient learning algorithms. Algorithms for learning rich Boolean function classes in online, Probably Approximately Correct, and exact learning models. Connections with computational complexity theory emphasized. Substantial course project or term paper required.

COMS E6261x or y Advanced cryptography
3 pts. Lect: 3. Professor Malkin.
Prerequisite(s): COMS W4261. A study of advanced cryptographic research topics such as: secure computation, zero knowledge, privacy, anonymity, cryptographic protocols. Concentration on theoretical foundations, rigorous approach, and provable security. Content varies between offerings. May be repeated for credit.

COMS E6291x or y Theoretical topics in computer science
3 pts. Lect: 3. Professor Servedio.
Prerequisite(s): Instructor’s permission. Concentration on some theoretical aspect of computer science. Content varies from year to year. May be repeated for credit.

EECS E6321y Advanced digital electronic circuits
3 pts. Lect: 2. Professor Seok.
Prerequisite(s): EECS E4321. Advanced topics in the design of digital integrated circuits. Clocked and nonclocked combinational logic styles. Timing circuits: latches and flip-flops, phase-locked loops, delay-locked loops. SRAM and DRAM memory circuits. Modeling and analysis of on-chip interconnect. Power distribution and power-supply noise. Clocking, timing, and synchronization issues. Circuits for chip-to-chip electrical communication. Advanced technology issues that affect circuit design. The class may include a team circuit design project.

COMS E6424x Hardware security
3 pts. Lect: 2. Professor Sethumadhavan.
Prerequisite(s): CSEE W3827 and COMS W3157; Recommended: CSEE W4824 and COMS W4187. Techniques for securing the foundational aspects of all computing devices and systems. Topics include hardware-up security, hardware supply chain trust and security, storing secrets in hardware, boot time trust and security, side channel attacks and defenses, hardware support for compartmentalization, fault attacks and defenses, hardware support to strengthen software: memory safety, control flow integrity, information flow tracking, diversity, obfuscation, anomaly detection. Hardware support for accelerating cryptography and applied cryptography.

CSEE W6600x or y From data to solutions
3 pts. Lect: 3. Professor Hirschberg or Chang.
Prerequisite(s): Familiarity with common data science methods and tools. Must be able to write coherent weekly summary. Intended for students interested in data science and interdisciplinary research. Covers problems in medical research, journalism, history, economics, business, English, psychology, and other areas amenable to computational approaches.

EECS E6690-6699x or y Topics in data driven analysis and computation
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): the instructor's permission. Selected advanced topics in data-driven analysis and computation. Content varies from year to year, and different topics rotate through the course numbers 6690 to 6699.

STCS GU6701x or y Foundations of graphical models
3 pts. Lect: 3. Professor Blei.
Prerequisite(s): Basic probability and statistics, calculus, and some optimization. Ability to write software to analyze data. Knowledge of programming language for statistics and machine learning, such as R or Python. PhD-level course on development and use of probability models. Covers mathematical properties, algorithms, and their application to real problems. In-depth understanding of cutting-edge modern probabilistic modeling. Weekly papers, assignments, and final project required.

COMS E6731y Humanoid robots
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): A course in at least one of the following: AI, robotics, computer graphics, or computer vision. Seminar on humanoid robots. Analysis of existing hardware and software platforms. Programming of multi-degree-of-freedom robots. Understanding sensor feedback in perceive-act-sense control paradigms. Task-level planning and reasoning. Final project includes implementing a humanoid robot task on either a simulated or physical robot.

COMS E6732x or y Computational imaging
3 pts. Lect: 3. Professor Nayar.
Prerequisite(s): COMS W4731 or instructor’s permission. Computational imaging uses a combination of novel imaging optics and a

computational module to produce new forms of visual information. Survey of the state-of-the-art in computational imaging. Review of recent papers on omnidirectional and panoramic imaging, catadioptric imaging, high dynamic range imaging, mosaicing and superresolution. Classes are seminars with the instructor, guest speakers, and students presenting papers and discussing them.

COMS E6733x or y 3D photography
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): Experience with at least one of the following topics: Computer graphics, computer vision, pixel processing, robotics or computer-aided design, or instructor's permission. Programming proficiency in C, C++, or JAVA. 3D Photography—the process of automatically creating 3D, texture-mapped models of objects in detail. Applications include robotics, medicine, graphics, virtual reality, entertainment and digital movies etc. Topics include 3D data acquisition devices, 3D modeling systems and algorithms to acquire, create, augment, manipulate, render, animate and physically build such models.

COMS E6734y Computational photography
3 pts. Lect: 3. Professor Belhumeur.
Prerequisite(s): COMS W4160, W4731, or a working knowledge of photography are recommended. Students should have knowledge in any of three core areas: computer vision, computer graphics, or photography. Computational techniques are used to produce a new level of images and visual representations. Topics include HDR imaging, feature matching using RANSAC, image mosaics, image-based rendering, motion magnification, camera lens arrays, programmable lighting, face detection, single and multiview geometry, and more.

COMS E6735y Visual databases
3 pts. Lect: 3. Professor Kender.
Prerequisite(s): COMS W3134, W3136, or W3137 (or equivalent). COMS W4731 and W4735 helpful but not required. Contact instructor if uncertain. The analysis and retrieval of large collections of image and video data, with emphasis on visual semantics, human psychology, and user interfaces. Low-level processing: features and similarity measures; shot detection; key frame selection; machine learning methods for classification. Middle-level processing: organizational rules for videos, including unedited (home, educational), semiedited (sports, talk shows), edited (news, drama); human memory limits; progressive refinement; visualization techniques; incorporation of audio and text. High-level processing: extraction of thematic structures; ontologies, semantic filters, and learning; personalization of summaries and interfaces; detection of pacing and emotions. Examples and demonstrations from commercial and research systems throughout. Substantial course project or term paper required.

COMS E6737x or y Biometrics
3 pts. Lect: 3. Professor Belhumeur.
Prerequisite(s): Background at the sophomore level in computer science, engineering, or like discipline. Corequisites: None. We will explore the latest advances in biometrics as well as the machine learning techniques behind them. Students will learn how these technologies work and how they are sometimes defeated. Grading will be based on homework assignments and a final project. There will be no midterm or final exam. Shares lectures with COMS W4737. Students taking COMS E6737 are required to complete additional homework problems and undertake a more rigorous final project. Students will only be allowed to earn credit for COMS W4737 or COMS E6737 but not both.

CSEE E6824y Parallel computer architecture
3 pts. Lect: 2. Professor Sethumadhavan.
Prerequisite(s): CSEE W4824. Parallel computer principles, machine organization and design of parallel systems including parallelism detection methods, synchronization, data coherence and interconnection networks. Performance analysis and special purpose parallel machines.

CSEE E6847y Distributed embedded systems
3 pts. Lect: 2.
Prerequisite(s): Any COMS W411X, CSEE W48XX, or ELEN E43XX course, or instructor’s permission. An interdisciplinary graduate-level seminar on the design of distributed embedded systems. System robustness in the presence of highly variable communication delays and heterogeneous component behaviors. The study of the enabling technologies (VLSI circuits, communication protocols, embedded processors, RTOSs), models of computation, and design methods. The analysis of modern domain-specific applications including on-chip micro-networks, multiprocessor systems, fault-tolerant architectures, and robust deployment of embedded software. Research challenges such as design complexity, reliability, scalability, safety, and security. The course requires substantial reading, class participation and a research project.

CSEE E6861y Computer-aided design of digital systems
3 pts. Lect: 2. Professor Nowick.
Prerequisite(s): (i) one semester of advanced digital logic (CSEE W4823 or equivalent, or instructor’s permission); and (ii) a basic course in data structures and algorithms COMS W3134, W3136, W3137, W3157, or equivalent, and familiarity with programming. Introduction to modern digital CAD synthesis and optimization techniques. Topics include modern digital system design (high-level synthesis, register-transfer level modeling, algorithmic state machines, optimal scheduling algorithms, resource allocation and binding, retiming), controller synthesis and optimization, exact and heuristic two-level logic minimization, advanced multilevel logic optimization, optimal technology mapping to library cells (for delay, power and area minimization), advanced data structures (binary decision diagrams), SAT solvers and their applications, static timing analysis, and introduction to testability. Includes hands-on small design projects using and creating CAD tools.

CSEE E6863x Formal verification of hardware and software systems
3 pts. Lect: 2. Professor Theobald or Ivancic.
Prerequisite(s): COMS W3134, W3136, or W3137 and COMS W3261. Introduction to the theory and practice of formal methods for the design and analysis of correct (i.e., bug-free) concurrent and embedded hardware/software systems. Topics include temporal logics; model checking; deadlock and liveness issues; fairness; satisfiability (SAT) checkers; binary decision diagrams (BDDs); abstraction techniques; introduction to commercial formal verification tools. Industrial state-of-the-art, case studies, and experiences: software analysis (C/C++/Java), hardware verification (RTL).

CSEE E6868x or y Embedded scalable platforms
3 pts. Lect: 2. Professor Carloni.
Prerequisite(s): CSEE W4868 or instructor's permission. Interdisciplinary graduate-level seminar on design and programming of embedded scalable platforms. Content varies between offerings to cover timely relevant issues and latest advances in system-on-chip design, embedded software programming, and electronic design automation. Requires substantial reading of research papers, class participation, and semester-long project.

EECS E6870x or y Speech recognition
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): Basic probability and statistics. Theory and practice of contemporary automatic speech recognition. Gaussian mixture distributions, hidden Markov models, pronunciation modeling, decision trees, finite-state transducers, and language modeling. Selected advanced topics will be covered in more depth.

COMS E6900x and y Tutorial in computer science
1–3 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. A reading course in an advanced topic for a small number of students, under faculty supervision.

COMS E6901x Projects in computer science
1–12 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Software or hardware projects in computer science. Before registering, the student must submit a written proposal to the instructor for review. The proposal should give a brief outline of the project, estimated schedule of completion, and computer resources needed. Oral and written reports are required. May be taken over more than one semester, in which case the grade will be deferred until all 12 points have been completed. No more than 12 points of COMS E6901 may be taken. Consult the department for section assignment.

COMS E6902x and y Thesis
1–9 pts. Members of the faculty.
Available to M.S. candidates. An independent investigation of an appropriate problem in computer science carried out under the supervision of a faculty member. A formal written

report is essential and an oral presentation may also be required. May be taken over more than one semester, in which case the grade will be deferred until all 9 points have been completed. No more than 9 points of COMS E6902 may be taken. Consult the department for section assignment.

COMS E6910x and y Fieldwork
1 pt. Members of the faculty.
Prerequisite(s): Obtained internship and approval from faculty adviser. Only for M.S. students in the Computer Science Department who need relevant work experience as part of their program of study. Final report required. May not be taken for pass/fail credit or audited.

CSEE E6915y Technical writing for computer scientists and engineers
3 pts. Members of the faculty.
Available to M.S. or Ph.D. candidates in CS/CE. Topics to help CS/CE and EE graduate students' communication skills. Emphasis on writing, presenting clear, concise proposals, journal articles, conference papers, theses, and technical presentations. Credit may not be used to satisfy degree requirements.

COMS E6998x and y Topics in computer science
3 pts. Members of the faculty.
Selected topics in computer science (advanced level). Content and prerequisites vary between sections and semesters. May be repeated for credit. Check "topics course" webpage on the department website for more information on each section.

COMS E6999x and y Topics in computer science, II
3 pts.
Prerequisite(s): COMS E6998. Continuation of COMS E6998.

COMS E9800x and y Directed research in computer science
1–15 pts. Members of the faculty.
Prerequisite(s): Submission of outline of proposed research for approval by faculty member who will supervise. The department must approve the number of points. May be repeated for credit. Only for Eng.Sc.D. candidates.

COMS E9910x and y Graduate research, I
1–6 pts. Members of the faculty.
Prerequisite(s): Submission of an outline of the proposed research for approval by the faculty member who will supervise. The department must approve the number of credits. May be repeated for credit. Only for M.S. candidates holding GRA or TA appointments. Note: It is NOT required that a student take Graduate research, I prior to taking Graduate research, II. Consult the department for section assignment.

COMS E9911x and y Graduate research, II
1-15 pts. Members of the faculty.
Prerequisite(s): Submission of an outline of the proposed research for approval by the faculty member who will supervise. The department must approve the number of points. May be repeated for credit. Only for M.S./Ph.D. track and Ph.D. students. Note: It is NOT required that a student take Graduate research, I prior to taking Graduate research, II. Consult the department for section assignment.

EARTH AND ENVIRONMENTAL ENGINEERING

Henry Krumb School of Mines
918 S. W. Mudd, MC 4711
212-854-2905
eee.columbia.edu

OUR MISSION

Earth and Environmental Engineering at the Henry Krumb School of Mines fosters excellence in education and research for the development and application of science and technology to maximize the quality of life for all, through the sustainable use and responsible management of Earth's resources. The department strives to provide education and carry out research that underpins the sustainable and equitable utilization of Earth's material, water, and energy resources at a scale that is beneficial to society. By leveraging cross-disciplinary opportunities afforded by the range of academic work in the department and the University, we tackle complex challenges that exist across the natural materials-water-energy-climate network of interdependencies.

DEPARTMENT CHAIR
Daniel Steingart

DIRECTOR OF FINANCE AND ADMINISTRATION
Jack Tomaselli

PROFESSORS
Kartik Chandran
George Deodatis
Pierre Gentine
Vjay Modi
Ismail C. Noyan
Daniel Steingart
Alan West

ASSOCIATE PROFESSOR
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ASSISTANT PROFESSORS
Adeyemi Adeleye
Shaina Kelly
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VISITING PROFESSOR
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PROFESSORS OF PROFESSIONAL PRACTICE
Raymond S. Farinato
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ADJUNCT PROFESSORS
Yuri Gorokhovich
Paul Knowles
Eric Rosenberg

PROFESSORS EMERITUS
Ponisseril Somasundaran

SENIOR RESEARCH SCIENTIST
Vasilis M. Fthenakis

ASSOCIATE RESEARCH SCIENTIST
Partha Patra

EARTH RESOURCES AND THE ENVIRONMENT

The Earth and Environmental Engineering program fosters education and research in the development and application of technology for the sustainable development, use, and integrated management of Earth's resources. Resources are identified as minerals, energy, water, air, and land, as well as the physical, chemical, and biological components of the environment. There is close collaboration with other engineering disciplines, the Lamont-Doherty Earth Observatory, the International Research Institute for Climate Prediction, the Center for Environmental Research and Conservation, and other Columbia Earth Institute units.

THE HENRY KRUMB SCHOOL OF MINES AT COLUMBIA UNIVERSITY

The department is the direct lineage of the School of Mines of Columbia University, which was the first mining and metallurgy school in the U.S. (1864). It became the foundation for Columbia's School of Engineering and Applied Science and later the home of the Department of Mining, Metallurgical and Mineral Engineering. However, the title "School of Mines" was retained by Columbia University honoris causa. You can see the bronze statue of The Metallurgist (Le Marteleur) in front of Columbia's Mudd Hall that was named after an alumnus of the School of Mines.

One century after its formation, the School of Mines was renamed Henry Krumb School of Mines (HKSM) in honor of the generous alumnus of the School of Mines and his wife, Lavon Duddleson Krumb. HKSM has been a leader in mining and metallurgy research and education, including the first mining handbook by Professor Peel, the first mineral processing handbook by Professor Taggart, and other pioneering work in mineral benefaction, chemical thermodynamics, kinetics, transport phenomena in mineral extraction and processing, ecological and environmentally responsible mining, and pursuit of state-of-the-art research advancing responsible use of Earth's resources. The Henry Krumb School of Mines located in The Fu Foundation School of Engineering and Applied Science offers students interested in mining and metallurgy the opportunity to focus their studies in these fields within the department of Earth and Environmental Engineering.

In 1986, HKSM was designated by Governor Cuomo as the mining and Mineral Resources Research Institute of the State of New York.

EARTH AND ENVIRONMENTAL ENGINEERING (EEE)

With the creation of the Earth Institute at Columbia University, a major initiative in the study of Earth, its environment and society, the traditional programs of HKSM in mining, mineral processing, and extractive metallurgy were expanded in the late nineties to encompass environmental concerns related to the use of materials, energy and water resources, and to reflect one of nine departments of SEAS with a focus on the development and application of technology for the sustainable development, use and integrated management of Earth's resources.

As a result of the vast developments in the technologies and fields of environmental management, in 1996 and 1998, respectively, the engineering school created the M.S. program in Earth Resources Engineering and the B.S. program in Earth and Environmental Engineering to meet the needs of a changed society. Students interested in the traditional disciplines of mining, mineral engineering and metallurgy continue to study these fields through

EARTH AND ENVIRONMENTAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3) **or** MATH UN1207 (4)	MATH UN1102 (3) MATH UN1208 (4)	APMA E2000 (4) and E2001 (0)	APMA E2101 (3) MATH UN2030 (3) ODE
PHYSICS	UN1401 (3) **or** UN1601 (3.5) **or** UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	CHEM UN2443 (3.5) **or** PHYS UN1403 (3) **or** PHYS UN2601 (3.5) **or** BIOL UN2005 (4)	EACE E4252 (3) Foundations of environmental engineering
CHEMISTRY	UN1403 (3.5) **and** Lab UN1500 (3) either semester **or** UN1604 (3.5) **or** UN2045 (3.5)	UN1404 (3.5) UN1507 (3) UN2046 (3.5) **and** Lab UN1507 (3)		
REQUIRED NONTECHNICAL ELECTIVES	ENGL CC1010 (3)		HUMA CC1001, COCI CC1101, **or** Global Core (3–4)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0) HUMA UN1121 **or** UN1123 (3)
REQUIRED PROFESSIONAL AND TECHNICAL ELECTIVES			EESC UN2100 (4.5) **or** EESC UN2200 (4.5) EEAE E2100 (3) A better planet by design	STAT GU4001 (3)
COMPUTER SCIENCE	ENGI E1006 (3) any semester			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

EARTH AND ENVIRONMENTAL ENGINEERING: THIRD AND FOURTH YEARS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	EAEE E3103 (3) Energy, minerals, and material systems	EAEE E4003 (3) Aquatic chemistry	EAEE E3998 (2) Undergraduate design project	EACE E3255 (3) Environmental control and pollution reduction systems
	EAEE E3200 (3) Applied transport and chemical rate phenomena	EACE E3250 (3) Hydrosystems engineering	EAEE E4160 (3) Solid and hazardous waste management	EAEE E3999 (2) Undergraduate design project
	CHEE E3010 (3) Principles of chemical engineering thermodynamics	EAEE E3800 (4) Earth and environmental engineering lab, I EAEE E3901 (3) Environmental microbiology		
TECHNICAL ELECTIVES		3 points	6 points	9 points
NONTECHNICAL ELECTIVES	3 points		3 points	6 points
TOTAL POINTS	12	16	14	20

the Earth and Environmental Engineering department course offerings as well as the course offerings through the Material Science and Engineering program.

The B.S. program in Earth and Environmental Engineering was initiated in the fall of 1998 to replace the mining/mineral/extractive metallurgy programs of HKSM and is now accredited by ABET.

The department builds upon this legacy every year through its core class and unofficial motto, "A Better Planet By Design," bringing together:

- water conservation, allocation, and decontamination
- climate change mitigation
- minerals, metals, and materials processing, extraction, and reuse
- waste and pollution prevention, mitigation and management
- renewable energy and carbon management

By bridging engineering scales from colloidal interfaces to resource distribution, the department now considers resource development both on Earth and off, with a new effort in space mining.

The EEE program warmly welcomes Combined Plan students. An EEE minor is offered to all Columbia engineering students who wish to enrich their academic record by concentrating some of their technical electives on Earth/Environment subjects.

RESEARCH CENTERS ASSOCIATED WITH EARTH AND ENVIRONMENTAL ENGINEERING

Center for Advanced Materials for Energy and Environment. The Center develops advanced materials to address challenges for closing the energy loop, carbon loop, and water loop.

Center for Life Cycle Analysis (CLCA). The Center for Life Cycle Analysis (CLCA) provides a framework for quantifying the potential environmental impacts of material and energy inputs and outputs of a process or product from “cradle to grave.” For more information visit clca.columbia.edu.

Columbia Climate School. For more information visit climate.columbia.edu.

Columbia Electrochemical Energy Center (CEEC). For more information visit ceec.engineering.columbia.edu.

Columbia Water Center. The Center was established in 2008 to address issues of Global Water Security. For more information visit water.columbia.edu.

Earth Engineering Center (EEC). EEC has concentrated on advancing the goals of sustainable waste management in the U.S. and globally. For more information visit earth.engineering.columbia.edu.

Industry/University Cooperative Research Center for Particulate and Surfactant Systems (CPaSS). The goals of CPaSS are to perform industrially relevant research to address the technological needs in commercial surfactant and polymer systems, develop new and more efficient surface-active reagents for specific applications in the industry and methodologies for optimizing their performance, promote the use of environmentally benign surfactants in a wide array of technological processes, and build a resource center to perform and provide state-of-the-art facilities for characterization of surface-active reagents. For more information visit blogs.cuit.columbia.edu/iucrc/.

Langmuir Center for Colloids and Interfaces (LCCI). This center brings together experts from mineral engineering, applied chemistry, chemical engineering, biological sciences, and chemistry to probe complex interactions of colloids and interfaces with surfactants and macromolecules.

Lamont-Doherty Earth Observatory (LDEO). For more information visit lamont.columbia.edu

Lenfest Center for Sustainable Energy (LCSE). The mission of the Lenfest Center for Sustainable Energy is to advance science and develop innovative technologies that provide sustainable energy for all humanity while maintaining the stability of Earth's natural systems. For more information visit energy.columbia.edu.

The Earth Institute. For more information visit earth.columbia.edu.

SCHOLARSHIPS, FELLOWSHIPS, AND INTERNSHIPS

The department arranges for undergraduate summer internships after the sophomore and junior years. Undergraduates can also participate in graduate research projects under the work-study program. Graduate research and teaching assistantships, as well as fellowships funded by the Department, are available to qualified graduate students. GRE scores are required of all applicants for graduate studies.

UNDERGRADUATE PROGRAM

The Bachelor of Science (B.S.) degree in Earth and Environmental Engineering prepares students for careers in the public and private sector concerned with primary materials (minerals, fuels, water) and the environment. Graduates are also prepared to continue with further studies in Earth/Environmental sciences and engineering, business, public policy, international studies, law, and medicine. The EEE program is accredited as an environmental engineering program by the Engineering Accreditation Commission of ABET, http://www.abet.org. Practice and theory are both critical to the advancement of earth and environmental engineering; the department works actively with students to reach their learning outcomes and research and career goals.

Undergraduate Program Objectives

1. Graduates equipped with the necessary tools (mathematics, chemistry, physics, earth sciences, and engineering science) will understand and implement the underlying principles used in the engineering of processes and systems.
2. Graduates will be able to pursue careers in industry, government agencies, and other organizations concerned with the environment and the provision of primary and secondary materials and energy, as well as continue their education as graduate students in related disciplines.
3. Graduates will possess the basic skills needed for the practice of Earth and Environmental Engineering, including measurement and control of material flows through the environment; assessment of environmental impact of past, present, and future industrial activities; and analysis and design of processes for remediation, recycling, and disposal of used materials.
4. Graduates will practice their profession with excellent written and communication skills and with professional ethics and responsibilities.

Undergraduate Student Outcomes

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

The Curriculum

The first two years of the EEE program are similar to those of other engineering programs. Students are provided with a strong foundation in basic sciences and mathematics, as well as the liberal arts core. Specific to the EEE program is an early and sustained introduction to earth science and environmental engineering, and options for a number of science courses to meet the specific interests of each student. The junior and senior years of the program consist of a group of required courses in engineering science and a broad selection of technical electives organized. The department website at eee.columbia.edu details the required courses and other information.

Several Columbia departments, such as Civil Engineering, Mechanical Engineering, and Earth and Environmental Sciences (Lamont-Doherty Earth Observatory), as well as the Mailman School of Public Health, contribute courses to the EEE program. EEE students are strongly encouraged to work as summer interns in industry or agencies on projects related to Earth and Environmental Engineering.

GRADUATE PROGRAMS

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

M.S. in Earth and Environmental Engineering (M.S.-EEE)

The M.S.-EEE program is designed for engineers and scientists who plan to pursue, or are already engaged in, environmental management/development careers. The focus of the program is the environmentally sound mining and processing of primary materials (minerals, energy, and water) to the recycling and proper disposal of used materials. The program also includes technologies for assessment and remediation of damages to the environment including water treatment, processing of mine tailings, and carbon capture, utilization and storage. Students can choose a pace that allows them to complete the M.S.-EEE requirements while being employed.

M.S.-EEE graduates are specially qualified to work for engineering, financial startup, and operating companies engaged in the earth resources development and environmental industries and technologies, environmental groups in all industries, and for city, state, and federal agencies responsible for the environment and energy/resource conservation. At the present time, the U.S. environmental industry comprises nearly 30,000 big and small businesses with total revenues of more than $150 billion. Sustainable development, climate change adaptation and mitigation, as well as environmental quality have become top priorities of government and industries in the United States and many other nations.

This M.S. program is offered in collaboration with the Departments of Civil Engineering and Earth and Environmental Sciences. Many of the teaching faculty are affiliated with Columbia's Earth Engineering Center. For students with a B.S. in engineering, at least 30 points (ten courses) are required. Students may carry out a research project (3 credits) or write a thesis worth 6 points. A number of areas of study are available for the M.S.-EEE, and students may choose courses that match their interest and career plans.

Additionally, there are three optional concentrations in the program, in each of which there are a number of required specific core courses and electives. The concentrations are described briefly below; details and the lists of specific courses for each track are available from the department. Students interested in a specific focus in Mining Engineering or related fields should consult their faculty adviser for relevant course listings.

Water Resources and Climate Risks

Climate-induced risk is a significant component of decision making for the planning, design, and operation of water resource systems, and related sectors such as energy, health, agriculture, ecological resources, and natural hazards control. Climatic uncertainties can be broadly classified into two areas: (1) those related to anthropogenic climate change; (2) those related to seasonal- to century-scale natural variations. Climate change impacts the design of physical, social, and financial infrastructure systems to support the sectors listed above. The climate variability and predictability issues impact systems operation, and hence design. The goal of the M.S. concentration in water resources and climate risks is to provide (1) a capacity for understanding and quantifying the projections for climate change and variability in the context of decisions for water resources and related sectors of impact; and (2) skills for integrated risk assessment and management for operations and design, as well as for regional policy analysis and management. Required classes include:

- EACE E4250 Hydrosystems Engineering
- EACE E4163 Sustainable water treatment and reuse
- EAEE E4257 Environmental data analysis and modeling

Sustainable Energy

Building and shaping the energy infrastructure of the twenty-first century is one of the central tasks for modern engineering. The purpose of the sustainable energy concentration is to expose students to modern energy technologies and infrastructures and to the associated environmental, health, and resource limitations. Emphasis will be on energy generation and use technologies that aim to overcome the limits to growth that are experienced today. Energy and economic well-being are tightly coupled. Fossil fuel resources are still plentiful, but access to energy is limited by environmental and economic constraints. A future world population of 10 billion people trying to approach the standard of living of the developed nations cannot rely on today's energy technologies and infrastructures without severe environmental impacts. Concerns over climate change and changes in ocean chemistry require reductions in carbon dioxide emissions, but most alternatives to conventional fossil fuels, including nuclear energy, are too expensive to fill the gap. Yet access to clean, cheap energy is critical for providing minimal resources: water, food, housing, and transportation.

Concentration-specific classes will sketch out the availability of resources, their geographic distribution, the economic and environmental cost of resource extraction, and avenues for increasing energy utilization efficiency, such as cogeneration, district heating, and distributed generation of energy. Classes will discuss technologies for efficiency improvement in the generation and consumption sector; energy recovery from solid wastes; alternatives to fossil fuels, including solar and wind energy, energy storage; and technologies for addressing the environmental concerns over the use of fossil fuels. Classes on climate change, air quality, and health impacts focus on the consequences of energy use. Policy and its interactions with environmental sciences and energy engineering will be another aspect of the concentration.

Additional specialization may consider region-specific energy development. Required classes include:
- EAEE E4002 Alternative energy resources
- EEEL E4220 Energy system economics and optimization

Sustainable Mining and Materials

Earth mineral and metal resources are the backbone of civilization and are critical to economic development and meeting the demands of a growing population. their development today faces several big challenges: (1) declining value content in the available ore bodies and poor quality of the resources; (2) increasing focus on safety and health risks, and environmental impacts; (3) inefficient and high energy and water consumption; (4) huge risks associated with waste generation and management.

It is well recognized in the earth resource development industry that the traditional processing paradigm is no longer sustainable and cannot address these serious challenges. The overall goal of industry to develop and implement technologies for sensible and sustainable use of earth resources is part of a "mines of the future" paradigm, which encompasses topics such as mine-to-metal integration, modular processing, digital optimization, machine learning and AI, sensors and chemometrics, benign process chemicals, and a host of other forward-looking concepts. A similar effort and outlook exists for urban mining and recycling. The transformation of waste to energy and the recovery of minerals from recycling streams are examples of these areas that EEE is a world leader in. The EEE program in Sustainable Mining and Materials integrates foundational engineering principles and processes with the transformational innovations under development in the earth resources management sector. Core classes include:
- EAEE E4160 Solid and hazardous waste management
- EAEE E4200 Introduction to sustainable production of earth mineral & metal resources
- EAEE E4228 Separation science and technology in sustainable earth resources development

M.S. in Carbon Management (MCM)

The program is designed to prepare students to create and implement multi-faceted solutions to the carbon problem with an in-depth understanding of the complexity and multidisciplinary nature of the issues.

Coursework includes 30 credits of graduate coursework. Depending on student's backgrounds, some undergraduate level science courses may be required. Each student will develop an academic plan with the program director. There are three options for completing the 30 credits:
- 30 credits of lecture courses
- 24 credits of lecture courses and 6 credits of research with a culminating Master's Thesis
- 27 credits of lecture courses and 3 credits of research with a concluding report

Core courses:
- EAEE E4300/E6212 Introduction to carbon management
- EAEE E4302 Carbon capture
- EAEE E4301 Carbon storage
- EAEE E4305 CO_2 utilization and conversion

Professional Degree; Engineer of Mines

The program is designed for engineers who wish to do advanced work beyond the level of the M.S. degree but who do not desire to emphasize research. Admissions requirements include Undergraduate engineering degree, minimum 3.0 GPA, and GRE.

Candidates must complete at least 30 credits of graduate work beyond the M.S., or 60 points of graduate work beyond the B.S. No thesis is required. All degree requirements must be completed within 5 years of the beginning of the first course credited toward the degree.

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

Core courses:
- EAEE E4001 Industrial ecology of earth resources
- EAEE E4009 Geographic information systems (GIS) for resource, environmental and infrastructure management

Elective courses must be six courses at the 4000 or higher level from within the Earth and Environmental Engineering Department, the Chemical Engineering Department, or others as approved by the adviser. These include but are not limited to: EAEE E4900, CHEE E4252, EACE E4252, EAEE E4257, ELEN E4004, EAEE E4160, EAEE E4300, EAEE E6132, EAEE E6140, EAEE E6150, EAEE E6212. Although not required, interested students may choose to complete up to six credits in EAEE E9309.

Doctoral Programs

EEE offers two doctoral degrees: (1) the Eng.Sc.D. degree, administered by Columbia Engineering; and (2) the Ph.D. degree, administered by the Graduate School of Arts and Sciences.

Doctoral Qualifying Examination and Research Proposal

Before the end of the first semester in the doctoral program, the student and their adviser will set up an advisory committee of two or three faculty members. This committee will meet at least once a semester to assess the academic and research progress of the student and to recommend corrective action in case of emerging or existing deficiencies.

Doctoral students are required to pass a qualifying exam within their first year into the program. They will submit and defend their research proposal approximately one year after successful completion of the qualifying exam. Submission of the dissertation and thesis defense will follow general University rules.

The qualifying examination will be an oral exam administered by three faculty members. The adviser of the student will be a member of the exam committee but may not be the chair. The students will be examined in their understanding of fundamentals as they apply in the areas of research of the department: water resources, materials processing, energy, and chemical and biochemical processes. It is expected that each question period will last about 20 minutes, of which 15 minutes will be led by the faculty member from the area and the remaining 5 minutes will be open for questions by all faculty present at the exam. There will be a final period of 20 minutes for general questions.

All graduate students are expected to have a background equivalent to the required core of our undergraduate program. They have, of course, an opportunity to make up for any deficiency in their master's program. In order to be prepared for the exam, students can take at least one course in each core area during their first two semesters at Columbia (see website for up-to-date course listing). In case the student declares an explicit minor in another department, the qualifying exam requirements will be modified in consultation with the graduate committee. The minor has to be approved by both departments.

The engineering objectives of EEE research and education include:

- Provision and disposal of materials: environmentally sustainable extraction and processing of primary materials; manufacturing of derivative products; recycling of used materials; management of industrial residues and used products; materials-related application of industrial ecology.
- Management of water resources: understanding, prediction, and management of the processes that govern the quantity and quality of water resources, including the role of climate; development/operation of water resource facilities; management of water-related hazards.
- Energy resources and carbon management: mitigation of environmental impacts of energy production; energy recovery from waste materials; advancement of energy efficient systems; new energy sources; development of carbon sequestration strategies.
- Sensing and remediation: understanding of transport processes at different scales and in different media; containment systems; modeling flow and transport in surface and subsurface systems; soil/water decontamination and bioremediation.

COURSES IN EARTH AND ENVIRONMENTAL ENGINEERING

EAEE E2100x A better planet by design
3 pts. Lect: 3. Professor Adeleye.
Introduction to design for a sustainable planet. Scientific understanding of the challenges. Innovative technologies for water, energy, food, materials provision. Multiscale modeling and conceptual framework for understanding environmental, resource, human, ecological, and economic impacts and design performance evaluation. Focus on the linkages between planetary, regional, and urban water, energy, mineral, food, climate, economic, and ecological cycles. Solution strategies for developed and developing country settings.

CHEE E3010x Principles of chemical engineering thermodynamics
3 pts. Lect: 3. Professor Simunovic.
Prerequisite(s): CHEM UN1403 or equivalent. Teaches the formal relationships in the physical world, connecting the fundamental principles with the basis of chemical engineering practice. Topics include the first and second laws of thermodynamics, concepts such as energy and entropy, the equations that relate heat to other forms of energy, properties of ideal and real gases, fluids, single and multicomponent systems, phase and chemical equilibria, and the practical implications of these phenomena to systems from the molecular scale to the living world.

EAEE E3101y Earth resource production systems
3 pts. Lect: 3. Not offered in 2024–2025.
Technologies and equipment common to a wide range of surface and subsurface engineering activities: mine reclamation, hazardous waste remediation, discovering and operating surface and underground mines, detection and removal of hidden underground objects, waste disposal, dredging and harbor rehabilitation, and tunneling for transportation or water distribution systems. These methods and equipment are examined as they apply across the spectrum from mining to environmental engineering projects. The aim is to provide a broad background for earth and environmental engineers in careers involving minerals and industrial, large-scale environmental projects.

EAEE E3103x Energy, minerals, and materials systems
3 pts. Lect: 3. Professor Farinato.
Prerequisite(s): MSAE E3111 or MECE E3301 and ENME E3161 or MECE E3100 or equivalent Corequisite(s)s: MSAE E3111 or MECE E3301 and ENME E3161 or MECE E3100 or equivalent. Overview of energy resources, resource management from extraction and processing to recycling and final disposal of wastes. Resources availability and resource processing in the context of the global natural and anthropogenic material cycles; thermodynamic and chemical conditions including nonequilibrium effects that shape the resource base; extractive technologies and their impact on the environment and the biogeochemical cycles; chemical extraction from mineral ores, and metallurgical processes for extraction of metals. In analogy to metallurgical processing, power generation and the refining of fuels are treated as extraction and refining processes. Large scale of power generation and a discussion of its impact on the global biogeochemical cycles.

MSAE E3141y Processing of metals and semiconductors
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E3103 or equivalent. Synthesis and production of metals and semiconductors with engineered microstructures for desired properties. Includes high-temperature, aqueous, and electrochemical processing; thermal and mechanical processing of metals and alloys; casting and solidification; diffusion, microstructural evolution, and phase transformations; modification and processing of surfaces and interfaces; deposition and removal of thin films. Processing of Si and other materials for elemental and compound semiconductor-based electronic, magnetic, and optical devices.

EAEE E3185y Summer fieldwork for earth and environmental engineers
0.5 pt. Not offered in 2024–2025.
Undergraduates in earth and environmental engineering may spend up to three weeks in the field under staff direction. The course consists of mine, landfill, plant, and major excavation site visits and brief instruction of surveying methods. A final report is required.

EAEE E3200x Applied transport and chemical rate phenomena
3 pts. Lect: 3. Professor Yip.
Prerequisite(s): APMA E2101. Fluid statics. Basics of flow analysis. Dimensional analysis. Pipe flow. Fluid dynamics, heat and mass transfer. Effects of velocity, temperature, and concentration gradients and material properties on fluid flow, heat and mass transfer. Applications to environmental engineering problems.

EAEE E3221x Environmental geophysics
3 pts. Lect: 3. Not offered in 2024–2025.
Introduction to applied and environmental geophysics methods. Overview of principles of geophysics, geophysical methods and techniques (seismic, ground penetrating radar, resistivity, frequency em, and magnetics), and theory and practical aspects of data processing and inversion. Examination of geophysical case studies for engineering and environmental purposes.

EACE E3250y Hydrosystems engineering
3 pts. Lect: 3. Professor Kelly.
Prerequisite(s): CHEN E3110 or ENME E3161 or equivalent, or instructor's permission. A quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for non-point source pollution. Spatial

hydrologic analysis using GIS and watershed models.

EACE E3255y Environmental control and pollution reduction systems
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): EAEE E3200 or ENME E3161 or MECE E3100. Sources of solid/gaseous air pollution and the technologies used for modern methods of abatement. Air pollution and its abatement from combustion of coal, oil, and natural gas and the thermodynamics of heat engines in power generation. Catalytic emission control is contrasted to thermal processes for abating carbon monoxide, hydrocarbons, oxides of nitrogen and sulfur from vehicles and stationary sources. Processing of petroleum for generating fuels. Technological challenges of controlling greenhouse gas emissions. Biomass and the hydrogen economy coupled with fuel cells as future sources of energy.

EAEE E3800y Earth and environmental engineering laboratory, I
4 pts. Lect: 1. Lab: 3. Professor Bourtsalas.
Prerequisite(s): CHEE E3010. Corequisite(s): EACE E3255. Experiments on fundamental aspects of earth and environmental engineering with emphasis on the applications of chemistry, biology and thermodynamics to environmental processes: energy generation, analysis and purification of water, environmental biology, and biochemical treatment of wastes. Students will learn the laboratory procedures and use analytical equipment firsthand, hence demonstrating experimentally the theoretical concepts learned in class.

EAEE E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Research training course. Recommended in preparation for laboratory-related research.

EAEE E3900x and y–S3900 Undergraduate research in earth and environmental engineering
0–3 pts. Directed study. Members of the faculty.
This course may be repeated for credit, but no more than 3 points of this course may be counted toward the satisfaction of the B.S. degree requirements. Candidates for the B.S. degree may conduct an investigation in Earth and Environmental Engineering, or carry out a special project under the supervision of EAEE faculty. Credit for the course is contingent on the submission of an acceptable thesis or final report. This course cannot substitute for the Undergraduate design project (EAEE E3999 or EAEE E3999).

EAEE E3901y Environmental microbiology
3 pts. Lect: 3. Professor Chandran.
Prerequisite(s): CHEM UN1404 or equivalent. Fundamentals of microbiology, genetics and molecular biology, principles of microbial nutrition, energetics and kinetics, application of novel and state-of-the-art techniques in monitoring the structure and function of microbial communities in the environment, engineered processes for biochemical waste treatment and bioremediation, microorganisms and public health, global microbial elemental cycles.

EAEE E3995x, y, and s Fieldwork
1 pt. Members of the faculty.
Prerequisite(s): Instructor's permission. Obtained internship and approval from faculty adviser. Written application must be made prior to registration outlining proposed internship and study program. Final reports required. May not be taken for pass/fail credit or audited. Fieldwork credits may not count toward any major core, technical elective, and nontechnical requirements. International students must also consult with the International Students and Scholars Office. Note: only for EAEE undergraduate students who need relevant off-campus work experience as a part of their program of study as determined by instructor.

EAEE E3998x-E3999y Undergraduate design project
2 pts. (each semester). Lect: 1. Lab: 2. Professor Farrauto.
Prerequisite(s): senior standing. Students must enroll for both 3998x and 3999y during their 4 year. Selection of an actual problem in earth and environmental engineering, and design of an engineering solution including technical, economic, environmental, ethical, health and safety, social issues. Use of software for design, visualization, economic analysis, and report preparation. Students may work in teams. Presentation of results in a formal report and public presentation.

EAEE E4000x Machine learning for environmental engineering and science
3 pts. Lect: 2.5. Professor Gentine.
Prerequisite(s): Computer language (Python or Julia), some linear algebra and machine learning. Aimed at understanding and testing state-of-the-art methods in machine learning applied to environmental sciences and engineering problems. Potential applications include but are not limited to remote sensing, and environmental and geophysical fluid dynamics. Includes testing "vanilla" ML algorithms, feedforward neural networks, random forests, shallow vs deep networks, and the details of machine learning techniques.

EAEE E4001x Industrial ecology of earth resources
3 pts. Lect: 3. Professor Bourtsalas.
Industrial ecology examines how to reconfigure industrial activities so as to minimize the adverse environmental and material resource effects on the planet. Engineering applications of methodology of industrial ecology in the analysis of current processes and products and the selection or design of environmentally superior alternatives. Home assignments of illustrative quantitative problems.

EAEE E4002y Alternative energy resources
3 pts. Lect: 3. Professor Steingart.
An engineering and economic analysis of past, present and future energy resources. Technological options and their role in the world energy markets. Understanding limits of energy and power density and its impact of resource adoption and feasibility. Comparison of renewable and non-renewable energy resources and analysis of the consequences of various technological choices and constraints. Economic considerations, energy availability, and the environmental consequences of large-scale, widespread use of each particular technology. Critical analysis of carbon dioxide capture and carbon dioxide disposal as a means of sustaining the fossil fuel options in comparison to dramatic increase of electrified resources.

EAEE E4003x Aquatic chemistry
3 pts. Lect: 3. Professor Yip.
Prerequisite(s): CHEE E3010. Principles of physical chemistry applied to equilibria and kinetics of aqueous solutions in contact with minerals and anthropogenic residues. The scientific background for addressing problems of aqueous pollution, water treatment, and sustainable production of materials with minimum environmental impact. Hydrolysis, oxidation-reduction, complex formation, dissolution and precipitation, predominance diagrams; examples of natural water systems, processes for water treatment and for the production of inorganic materials from minerals.

EAEE E4004x Physical processing and recovery of solids
3 pts. Lect: 3. Not offered in 2024–2025.
Generalized treatment of processes for solids separation. Applications to materials processing and handling; mining; solid waste, recycling, and resource recovery; construction materials and debris; scrap materials, yard and park wastes. Economic considerations and context. Relevant materials properties and bulk materials analyses. Process system flow-sheets and analysis. Solid/solid, solid/liquid, and solid/gas separation process. Liberation, concentration, and auxiliary processes. Design of separation machines: types and intensities of force involved; scaling-up factors. Laboratory demonstrations and a field trip will be included.

EAEE E4005x Near-surface engineering geophysics
3 pts. Lect: 3. Not offered in 2024–2025.
Geophysical methods as applicable to engineering problems. Principles of geophysics and noninvasive imaging techniques (inversion technology) and benefits and pitfalls of geophysics vs. direct imaging methods. Discussion of theory of each method. Discussion of data acquisition, processing and interpretation for each method. Treatment of several case studies. Class-wide planning and execution of small-scale geophysical survey.

EAEE E4007y Environmental geophysics field studies
3 pts. Lect: 3. Not offered in 2024–2025.
Application of geophysical methods to noninvasive assessment of the near surface. First part consists of series of two-hour lectures of physics and math involved in instrumental methods and data acquisition and processing. The field (nine field days) students plan surveys; collect and analyze geophysical data in teams; learn how to integrate geophysical data

with invasive data, hydrological, geological, engineering, and contaminant transport models; and develop a comprehensive and justifiable model of the subsurface. Geophysical methods include GPR (Ground Penetrating Radar), conductivity, and magnetic and seismic methods. Field applications include infrastructure/environmental assessment, archeological studies, and high resolution geology.

EAEE E4009x Geographic information systems (GIS) for resource, environmental and infrastructure management
3 pts. Lect: 3. Professor Gorokhovich.
Prerequisite(s): Instructor's permission. Basic concepts of spatial data representation and organization, and analytical tools are introduced and applied in a form of case studies from hydrology, environmental conservation, and emergency response to natural or man-made hazards, among others. Technical content includes geographic topics (map projections, cartography, etc.), spatial statistics, database design and use, interpolation and visualization of spatial surfaces and volumes, and multicriteria decision analysis. Students will learn the basics of ArcGIS Pro, Model Builder, and Python. Elective term projects or final exams emphasize spatial information synthesis toward the solution of a specific problem.

EAEE E4010y Remote sensing and environmental change
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): EAEE E4009 or EESC GU4050 or instructor's permission. Practical and theoretical foundations for the application of remote sensing techniques to identification and monitoring of environmental change. Designing and applying spectral indices for assessment and monitoring, time series analysis of remote sensing data for analyzing environmental problems. Discussions of published literature relevant to the central topic covered in class. Analysis of remote sensing data using IRI data library.

EAEE E4011y Industrial ecology for manufacturing
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): EAEE E4001 or instructor's permission. Application of industrial ecology to Design for Environment (DFE) of processes and products using environmental indices of resources consumption and pollution loads. Introduction of methodology for Life Cycle Assessment (LCA) of manufactured products. Analysis of several DFE and LCA case studies. Term project required on use of DFE/LCA on a specific product/process: (a) product design complete with materials and process selection, energy consumption, and waste loadings; (b) LCA of an existing industrial or consumer product using a commercially established method.

CHEE E4050x Industrial and environmental electrochemistry
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEN E3010 or equivalent. A presentation of the basic principle underlying electrochemical processes. Thermodynamics, electrode kinetics, and ionic mass transport. Examples of industrial and environmental applications illustrated by means of laboratory experiments: electroplating, refining, and winning in aqueous solutions and in molten salts; electrolytic treatment of wastes; primary, secondary, and fuel cells.

EAEE E4100x Better planet by design
3 pts. Lect: 3. Professor Bourtsalas.
Foundational for the Master of Science in Earth and Environmental Engineering degree. Provides broader understanding of engineering tools critical/essential to success in large-scale, engineering projects. Divided into two parts: Module on global/regional flows, and systems approach, and Module on Engineering Principles in Earth & Environmental Engineering. Guest lectures on several topics will be provided.

ECIA W4100y Management and development of water systems
3 pts. Lect: 3. Not offered in 2024–2025.
Decision analytic framework for operating, managing, and planning water systems, considering changing climate, values and needs. Public and private sector models explored through U.S.-international case studies on topics ranging from integrated watershed management to the analysis of specific projects for flood mitigation, water and wastewater treatment, or distribution system evaluation and improvement.

CIEE E4116x Energy harvesting
3 pts. Lect: 3. Professor Yin.
Prerequisite(s): ENME E3114 or equivalent, or instructor's permission. Criterion of energy harvesting, identification of energy sources. Theory of vibrations of discrete and continuous system, measurement and analysis. Selection of materials for energy conversion, piezoelectric, electromagnetic, thermoelectric, photovoltaic, etc. Design and characterization, modeling and fabrication of vibration, motion, wind, wave, thermal gradient, and light energy harvesters; resonance phenomenon, power electronics and energy storage and management. Applications to buildings, geothermal systems, and transportation.

CHEE E4140x Engineering separations processes
3 pts. Lect: 3. Professor Durning.
Prerequisite(s): CHEN E3100, E3120, and E3210 or instructor's permission. Design and analysis of unit operations employed in chemical engineering separations. Fundamental aspects of single and multistaged operations using both equilibrium and rate-based methods. Examples include distillation, absorption and stripping, extraction, membranes, crystallization, bioseparations, and environmental applications.

EAEE E4150y Air pollution prevention and control
3 pts. Lect: 3. Not offered in 2024–2025
Adverse effects of air pollution, sources and transport media, monitoring and modeling of air quality, collection and treatment techniques, pollution prevention through waste minimalization and clean technologies, laws, regulations, standards, and guidelines.

EAEE E4160y Solid and hazardous waste management
3 pts. Lect: 3. Professor Bourtsalas.
Generation, composition, collection, transport, storage and disposal of solid and hazardous waste. Impact on the environment and public health. Government regulations. Recycling and resource recovery.

EACE E4163y Sustainable water treatment and reuse
3 pts. Lect: 3. Professor Knowles.
Prerequisite(s): Introductory chemistry (with lab) and fluid mechanics, or the equivalent. Theory and application of the physical and chemical processes for treating potable water and reusing wastewater. Disinfection/oxidation, coagulation and flocculation, clarification, filtration, ion exchange, adsorption, membrane processes, advanced oxidation processes, activated sludge, and anaerobic sludge digestion.

EAEE E4180y Electrochemical energy storage systems
3 pts. Lect: 3. Professor Steingart.
Prerequisite(s): CHEM UN1403-1404 or equivalent, MECE E3301 or equivalent, PHYS UN1402 or equivalent. Corequisite(s): CHEN E4201, EAEE E3103. Survey course on electrochemical energy storage with a focus on closed-form cells. Fundamentals of thermodynamics will be reviewed and fundamentals of electrochemistry introduced. Application of fundamentals to devices such as batteries, flow batteries, and fuel cells. Device optimization with respect to energy density, power density, cycle life, and capital cost will be considered.

EAEE E4190x Photovoltaic systems engineering and sustainability
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Senior standing or instructor's permission. A systems approach for intermittent renewable energy involving the study of resources, generation, demand, storage, transmission, economics and politics. Study of current and emerging photovoltaic technologies, with focus on basic sustainability metrics (e.g., cost, resource availability, and life-cycle environmental impacts). The status and potential of first- and second-generation photovoltaic technologies (e.g., crystalline and amorphous Si, CdTe, CIGS) and emerging third-generation ones. Storage options to overcome the intermittency constraint. Large scales of renewable energy technologies and plug-in hybrid electric cars.

EAEE E4200y Introduction to sustainable production of earth mineral & metal resources
3 pts. Lect: 3. Professors Nagaraj.
Prerequisite(s): EAEE E3103 and undergraduate level courses in chemistry (especially inorganic, physical and organic). Introductory course focused on engineering principles and unit operations involved in sustainable processing of primary and secondary earth mineral and metal resources. Covers entire value chain, viz, aspects of economic resource deposits, mining,

fundamental principles and processes for size reduction, separations based on physical and chemical properties of minerals and metals, solid-liquid separation, waste and pollution management, water and energy efficiency and management, safety and health, environmental impact assessment and control, and economic efficiency. Special emphasis on concepts and practical applications within "mines of the future" framework to highlight innovations and transformational technological changes in progress.

EAIA W4200y Alternative energy resources
3 pts. Lect: 3. Professor Steingart.
Unconventional, alternative energy resources. Technological options and their role in the world energy markets. Comparison of conventional and unconventional, renewable and nonrenewable, energy resources and analysis of the consequences of various technological choices and constraints. Economic considerations, energy availability, and the environmental consequences of large-scale, widespread use of each particular technology. Introduction to carbon dioxide disposal as a means of sustaining the fossil fuel option. Recitation section required.

EAEE E4210x Thermal treatment of waste and biomass materials
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E3010 or the equivalent or instructor's permission. Origins, quantities generated, and characterization of solid wastes. Chemical and physical phenomena in the combustion or gasification of wastes. Application of thermal conversion technologies, ranging from combustion to gasification and pyrolysis. Quantitative description of the dominant waste to energy processes used worldwide, including feedstock preparation, moving grate and fluid bed combustion, heat transfer from combustion gases to steam, mitigation of high-temperature corrosion, electricity generation, district heating, metal recovery, emission control, and beneficial use of ash residues.

EEEL E4220x Energy system economics and optimization
3 pts. Lect: 3. Professor Xu.
Prerequisite(s): Basic linear algebra, basic probability and statistics, and basic programming skills. Fundamental of power system economics over which the current electricity markets are designed. Formulation of unit commitment and economic dispatch as mathematical optimization. Modeling of thermal generators, renewable generators, energy storage, and other grid resources in power system optimization. Introduction of equilibriums in electricity markets. Introduction of ancillary service markets. Overview of current energy system research topics. Designed for master's and doctoral students, but is also open to undergraduates with the appropriate foundation classes.

EAEE E4222y Interfacial engineering for sustainable energy and materials
3 pts. Lect: 3. Professor Farinato.
Prerequisite(s): EAEE E3103 or equivalent or instructor's permission. Cross-disciplinary interfacial engineering principles and applications in sustainable energy and material science. Surface science and systems analysis across different technology sectors—material production and processing, waste management, device manufacture, composites, coatings, ceramics, membranes, biomaterials, and microelectronics.

EAEE E4228y Separation science and technology in sustainable earth resources development
3 pts. Lect: 3. Professors Nagaraj.
Prerequisite(s): EAEE E3103 and undergraduate level courses in chemistry (especially inorganic, physical and organic). Recommended: EAEE E4252, EAEE E4003, and EAEE E4200. Detailed study of the chemical and physicochemical principles underlying separations in development of earth resources in a safe and sustainable manner. Covers wide-range of solid-solid, solid-liquid and liquid-liquid separations used in processing of mineral resources. Interfacial science and engineering principles of important industrial processes of flotation, flocculation, dewatering, interfacial transport, magnetic/gravity/electrostatic separations, solvent extraction, solid-support extraction, crystallization and precipitation. Emphasis on concepts in interfacial chemistry and concepts associated with 'mines of the future' framework.

EAEE E4241x Solids handling and transport systems
3 pts. Lect: 3. Not offered in 2024–2025.
Analysis and design of transportation systems for bulk solids in tunnels, mines, and large excavations. Design of hoisting, cable transport, rail and trackless haulage systems, conveyor belts, selection of loaders, excavators, off-highway trucks, and draglines for large excavations.

EACE E4250x or y Hydrosystems engineering
3 pts. Lect: 3. Professors Gentine and Kelly.
Prerequisite(s): CHEN E3110 or ENME E3161 or equivalent, or instructor's permission. Quantitative introduction to hydrologic and hydraulic systems, with a focus on integrated modeling and analysis of the water cycle and associated mass transport for water resources and environmental engineering. Coverage of unit hydrologic processes such as precipitation, evaporation, infiltration, runoff generation, open channel and pipe flow, subsurface flow and well hydraulics in the context of example watersheds and specific integrative problems such as risk-based design for flood control, provision of water, and assessment of environmental impact or potential for non-point source pollution. Spatial hydrologic analysis using GIS and watershed models.

CHEE E4252x Introduction to surface and colloid chemistry
3 pts. Lect: 3. Professors Farinato and Somasundaran.
Prerequisite(s): Elemental physical chemistry. The principles of surfaces and colloid chemistry critical to range of technologies indispensable to modern life. Surface and colloid chemistry has significance to life sciences, pharmaceuticals, agriculture, environmental remediation and waste management, earth resources recovery, electronics, advanced materials, enhanced oil recovery, and emerging extraterrestrial mining. Topics include: thermodynamics of surfaces, properties of surfactant solutions and surface films, electrokinetic phenomena at interfaces, principles of adsorption and mass transfer and modern experimental techniques. Leads to deeper understanding of interfacial engineering, particulate dispersions, emulsions, foams, aerosols, polymers in solution, and soft matter topics.

EACE E4252y Foundations of environmental engineering
3 pts. Lect: 3. Professor Chandran.
Prerequisite(s): CHEM UN1403, or equivalent; ENME E3161 or equivalent, or instructor's permission. Engineering aspects of problems involving human interaction with the natural environment. Review of fundamental principles that underlie the discipline of environmental engineering, i.e. constituent transport and transformation processes in environmental media such as water, air, and ecosystems. Engineering applications for addressing environmental problems such as water quality and treatment, air pollution emissions, and hazardous waste remediation. Presented in the context of current issues facing the practicing engineers and government agencies, including legal and regulatory framework, environmental impact assessments, and natural resource management.

EAEE E4255x River and coastal hydrodynamics
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEN E3110 or ENME E3161 or the equivalent. Dynamics of flow and waves in rivers and coastal settings, with applications to flooding and mixing of saline and fresh waters, sediment transport. Integrative hydrodynamics modeling experience using numerical and analytical tools applied to complex real world setting, including concerns of anthropogenic change in rivers and estuaries and sea level fluctuations at the river-estuary boundary.

CIEE E4257y Groundwater contaminant transport and remediation
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): EACE E3250 or equivalent. Sources and types of groundwater contamination. Groundwater hydrology. Groundwater contaminant rate and transport. Flow and transport in the unsaturated zone. Nonaqueous phase liquids and multiphase flow. Physical and numerical models for contaminant transport. Characterization and assessment of contaminated sites. Groundwater remediation alternatives. Regulations.

EAEE E4257y Environmental data analysis and modeling
3 pts. Lect: 3. Professor Xu.
Prerequisite(s): IEOR E3658, E4150, or STAT GU4001 or equivalent; some exposure to linear algebra; basic programming experiences.

Introduction parametric and nonparametric statistical models applied to climate and environmental data analysis. Time and space data analysis methods will be focused, including clustering, autoregressive models, trend analysis, Bayesian analysis, missing data imputation, geostatistics, and principal components analysis. Application to problems of climate variation and change; hydrology; air, water and soil pollution dynamics; disease propagation; ecological change; and resource assessment. The class requires the use of R with hands-on programmings and a term project applied to a current environmental data analysis problem.

EAEE E4262y Space exploration and mining
3 pts. Lect: 3. Professor Somasundaran.
Needs and opportunities for space exploration and mining, resources in planets and asteroids, history of human colonization, terraforming Mars, Titan, and the moon, safety and health issues, benign mining, space junk extraction, microbial mining.

EAEE E4280y Issues facing the water industry
3 pts. Lect: 3. Professors Becker.
Principles and practice of water treatment and utility management will be presented. Project-based class where students will work in teams to solve an issue for a water utility. Variety of external experts will lecture and serve as a resource for students for the project. Allows students to better understand the role of the water utility in providing safe drinking water in a sustainable manner. Students will become familiar with the challenges facing water utilities, gain knowledge in the design and operation of water treatment systems, and learn how to develop solutions to water supply and water quality issues that will allow them to pursue productive careers in the consulting, utility, or regulatory fields.

EAEE E4300x or y Introduction to carbon management
3 pts. Lect: 3. Professor Park.
Prerequisite(s): Undergraduate level mathematics and science, or instructor’s permission. Introduction to natural and anthropogenic carbon cycle, and carbon and climate. Rationale and need to manage carbon and tools with which to do so (basic science, psychology, economics and policy background, negotiations and society; emphasis on interdisciplinary and inter-dependent approach). Simple carbon emission model to estimate the impacts of a specific intervention with regard to national, per capita, and global emissions. Student-led case studies (e.g., reforestation, biofuels, CCS, efficiency, alternative energy) to illustrate necessary systems approach required to tackle global challenges.

EAEE E4301y Carbon storage
3 pts. Lect: 3. Professor Kelly and Kelemen.
Prerequisite(s): Undergraduate level mathematics and science, or instructor’s permission. Quantitative introduction to storage of carbon derived from greenhouse gases, mainly CO2, with a focus on geological carbon storage and mineralization in saline aquifers, depleted hydrocarbon reservoirs, and “reactive” subsurface formations (rocks rich in Fe, Ca, and Mg) as well and other natural and engineered storage reservoirs (e.g., terrestrial storage, ocean storage, building materials). Covers fundamental processes such as geochemical fluid-rock interactions and fluid flow, transport, and trapping of supercritical and/or dissolved CO2 in the context of pore-scale properties to field-scale example storage reservoirs and specific integrative problems such as reservoir characterization and modeling techniques, estimating storage capacity, and regulations and monitoring.

EAEE E4302x or y Carbon capture
3 pts. Lect: 3. Professor Bourtsalas.
Prerequisite(s): Undergraduate level math and science or instructor’s permission. Major technologies to store carbon dioxide, geological, ocean, and in the carbon chemical pool. Carbon dioxide transport technologies also covered. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE E4303x or y Carbon measurement and monitoring
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Undergraduate level math and science or instructor permission. Sources of various GHGs (whether fossil/industrial or biogenic), their chemical behavior, interactions, and global warming potential once airborne; available measurement, monitoring, and detection technologies to track gas emissions, including leakage from storage sites. Carbon accounting and reporting methodologies such as life cycle analysis, and corporate carbon footprinting. In addition to basic science and engineering challenges of each technology, full spectrum of economic, environmental, regulatory, and political/policy aspects, and their implication for regional and global carbon management strategies of the future. Combination of lectures, class debates and breakout groups, student presentations, and independent final projects.

EAEE E4304x Closing the carbon cycle
3 pts. Lect: 3. Professor Eisenberger.
Prerequisite(s): Calculus, basic inorganic chemistry, and basic physics, including thermodynamics, or instructor’s permission. Introduction to complex systems, their impact on our understanding and predictability of the carbon cycle, the use of systems analysis and modeling tools, as well as Bayesian statistics and decision theory for evaluating various solutions to close the carbon cycle, a detailed examination of the geochemical carbon cycle, major conceptual models that couple its changes to climate change, analysis of the anthropogenic carbon sources and sinks and role of carbon in energy production, closing the carbon cycle impacts on energy security, economic development and climate change protection, analysis of solutions to close the carbon cycle.

EAEE E4305y Carbon utilization and conversion
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): Undergraduate level thermodynamics or instructor's permission. Introduction to various CO_2 utilization and conversion technologies that can reduce the overall carbon footprint of commodity chemicals and materials. Fundamentals of thermodynamics, fluid mechanics, reaction kinetics, catalysis and reactor design will be discussed using technological examples such as enhanced oil recovery, shale fracking, photo and electrochemical conversion of CO_2 to chemical and fuels, and formation of solid carbonates and their various uses. Life cycle analyses of potential products and utilization schemes will also be discussed, as well as the use of renewable energy for CO_2 conversion.

EAEE E4350x Planning and management of urban hydrologic systems
3 pts. Lect: 3. Professor Rosenberg.
Prerequisite(s): ENME E3161 or equivalent. Introduction to runoff and drainage systems in an urban setting, including hydrologic and hydraulic analyses, flow and water quality monitoring, common regulatory issues, and mathematical modeling. Applications to problems of climate variation, land use changes, infrastructure operation and receiving water quality, developed using statistical packages, public-domain models, and Geographical Information Systems (GIS). Team projects that can lead to publication quality analyses in relevant fields of interest. Emphasis on the unique technical, regulatory, fiscal, policy, and other interdisciplinary issues that pose a challenge to effective planning and management of urban hydrologic systems.

EAEE E4361y Economics of earth resource industries
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): EAEE E3103 or instructor’s permission. Definition of terms. Survey of earth resource industries: resources, reserves, production, global trade, consumption of mineral commodities and fuels. Economics of recycling and substitution. Methods of project evaluation: estimation of operating costs and capital requirements, project feasibility, risk assessment, and environmental compliance. Cost estimation for reclamation/remediation projects. Financing of reclamation costs at abandoned mine sites and waste-disposal postclosure liability.

CHEE E4530y Corrosion of metals
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEN E3010 or equivalent. The theory of electrochemical corrosion, corrosion tendency, rates, and passivity. Application to various environments. Cathodic protection and coatings. Corrosion testing.

EAEE E4550x Catalysis for emissions control
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): One year of general college chemistry. Fundamentals of heterogeneous catalysis including modern catalytic preparation techniques. Analysis and design of catalytic emissions control systems. Introduction to current industrial catalytic solutions for controlling

gaseous emissions. Introduction to future catalytically enabled control technologies.

EAEE E4560y Particle technology
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ENME E3161 and MSAE E3111 or equivalent. Introduction to engineering processes involving particulates and powders. The fundamentals of particle characterization, multiphase flow behavior, particle formation, processing and utilization of particles in various engineering applications with examples in energy- and environment-related technologies. Engineering of functionalized particles and design of multiphase reactors and processing units with emphasis on fluidization technology. Particle technology is an interdisciplinary field. Due to the complexity of particulate systems, particle technology is often treated as art rather than science. In this course, the fundamental principles governing the key aspects of particle science and technology are introduced along with various industrial examples.

EAEE E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

EAEE E4901y Environmental microbiology
3 pts. Lect: 3. Professor Chandran.
Basic microbiological principles; microbial metabolism; identification and interactions of microbial populations responsible for the biotransformation of pollutants; mathematical modeling of microbially mediated processes; biotechnology and engineering applications using microbial systems for pollution control.

EAEE E4950x Environmental biochemical processes
3 pts. Lect: 3. Professor Chandran. Offered only in odd years.
Prerequisite(s): EAEE E4901, E4003, EACE E4252, or instructor's approval. Qualitative and quantitative considerations in engineered environmental biochemical processes. Characterization of multiple microbial reactions in a community and techniques for determining associated kinetic and stoichiometric parameters. Engineering design of several bioreactor configurations employed for biochemical waste treatment. Mathematical modeling of engineered biological reactors using state-of-the-art simulation packages.

EAEE E4999x and y Fieldwork
1 pt. Members of faculty.
Prerequisite(s): Instructor's written permission. Only EAEE graduate students who need relevant off- campus work experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed study program. Final reports required. This course may not be taken for pass/fail credit or audited. International students must also consult with the International Students and Scholars Office.

EAEE E6000x or y Special topics in earth and environmental engineering
3 pts. Lect: 3. Professor Gentine.
Current topics in earth and environmental engineering. Subject matter will vary by year. Instructors may impose prerequisites depending on the topic.

EAEE E6132y Numerical methods in geomechanics
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): EAEE E3112 and CIEN E4241 or instructor's permission. A detailed survey of numerical methods used in geomechanics, emphasizing the Finite Element Method (FEM). Review of the behavior of geological materials. Water and heat flow problems. FEM techniques for solving nonlinear problems, and simulating incremental excavation and loading on the surface and underground.

EAEE E6140y Environmental physicochemical processes
3 pts. Lect: 3. Professor Yip.
Prerequisite(s): EACE E4252 and EACE E4163 or the equivalent, or the instructor's permission. Fundamentals and applications of key physicochemical processes relevant to water quality engineering (such as water treatment, waste water treatment/reuse/recycling, desalination) and the natural environment (e.g., lakes, rivers, groundwater).

EAEE E6150y Industrial catalysis
3 pts. Lect: 3. Professor Farrauto.
Prerequisite(s): EAEE E4550 or equivalent, or instructor's permission. Fundamental principles of kinetics, characterization and preparation of catalysts for production of petroleum products for conventional transportation fuels, specialty chemicals, polymers, food products, hydrogen and fuel cells and the application of catalysis in biomass conversion to fuel. Update of the ever changing demands and challenges in environmental applications, focusing on advanced catalytic applications as described in modern literature and patents.

EAEE E6151y Applied geophysics
3 pts. Lect: 3. Not offered in 2024–2025.
Potential field data, prospecting, wave equations. Huygens' principle, Green's functions, Kirchoff equation, WKB approximation, ray tracing. Wave propagation, parameters. Computer applications. Wavelet processing, filters and seismic data. Stratified Earth model, seismic processing and profiling. Radon transform and Fourier migration. Multidimensional geological interpretation.

EAEE E6181x Advanced electrochemical energy storage
3 pts. Lect: 3. Professor Steingart.
Prerequisite(s): EAEE E4180, EAEE E4002. Most modern commercial implementations of electrochemical energy storage are not fully deterministic: provides context and best-hypotheses for modern challenges. Topics include: current understanding of lithium/lithium anode solid-electrolyte-interphase, reversible and irreversible side reactions in redox flow systems, electrochemically correlated mechanical fracture at multiple scales, relationships between electrolyte solvation and electrode insertion, roughening, smoothing, and detachment behavior of metal anodes, best practices in structural, chemical, and microscopic characterization, morphological vs. macro-homogenous transport models, particle to electrode to cell non-linearity.

EAIA W6201x or y Complexity science
4 pts. Lect: 4. Professors Castner, Dumas, Lall, Mutter, and Rising.
Prerequisite(s): Graduate standing and instructor's permission. Survey of techniques, applications, and implications of complexity science and complex systems. Topics include systems dynamics, chaos, scaling, fat-tailed distributions, fractals, information theory, emergence, criticality, agent-based models, graph theory, and social networks. Applications will cover climate science, ecology, conflict, hydrology, geomorphology, physics, social theory, epidemiology, and governance.

EAEE E6212y Carbon sequestration
3 pts. Lect: 3. Professor Park.
Prerequisite(s): EAEE E3200 or equivalent or instructor's permission. New technologies for capturing carbon dioxide and disposing of it away from the atmosphere. Detailed discussion of the extent of the human modifications to 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 of carbon dioxide. Engineering issues in their implementation, economic impacts, and the environmental issues raised by the various methods.

CHEE E6220y Equilibria and kinetics in hydrometallurgical systems
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E4050 or EAEE E4003. Detailed examination of chemical equilibria in hydrometallurgical systems. Kinetics and mechanisms of homogeneous and heterogeneous reactions in aqueous solutions.

EAEE E6228y Theory of flotation
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E4252 or instructor's permission. A detailed study of the physicochemical principles of the flotation process.

CHEE E6252y Advanced surface and colloid chemistry
3 pts. Lect: 2. Lab: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E4252. Applications of surface chemistry principles to wetting, flocculation, flotation, separation techniques, catalysis, mass transfer, emulsions, foams, aerosols, membranes, biological surfactant systems, microbial surfaces, enhanced oil recovery, and pollution problems. Appropriate individual experiments and projects. Lab required.

EAEE E6255x-E6256y Methods and applications of analytical decision making in

mineral industries
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Instructor's permission. Advanced study of decision-making problems with critical survey and applications of quantitative decision-making techniques in mineral industries. Systematic development of methods of the formulation, analysis, and resolution of these problems.

EAEE P6329x or y Water, sanitation, and human health
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Instructor's permission. In-depth analysis of issues relating to water, sanitation, and hygiene in both the developed and developing worlds. Hydrologic cycle, major causes of enteric morbidity and mortality, and design, financing and implementation of sanitation systems. For both engineering and public health students; intended to foster dialog between the two communities.

EAEE E8229x Selected topics in processing minerals and wastes
3 pts. Lect: 2. Lab: 3. Not offered in 2024–2025.
Prerequisite(s): CHEE E4252 or instructor's permission. Critical discussion of current research topics and publications in the area of flotation, flocculation, and other mineral processing techniques, particularly mechanisms of adsorption, interactions of particles in solution, thinning of liquid films, and optimization techniques.

EAEE E8231y Selected topics in hydro- and electrometallurgy
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): EAEE E4003 and CHEE E4050, or instructor's permission. Review of current research and literature in the field of hydrometallurgy, electrometallurgy, and corrosion. Topics will be selected by the instructor to illustrate the application of thermodynamics and rate phenomena to the design and control of electrochemical engineering processes.

EAEE E8233x and y Research topics in particle processing
0 pts. Professor Somasundaran.
Emergent findings in the interactions of particles with reagents and solutions, especially inorganics, surfactants, and polymers in solution, and their role in grinding, flotation, agglomeration, filtration, enhanced oil recovery, and other mineral processing operations.

EAEE E8273x-E8274y Mining engineering reports
0–4 pts. Not offered in 2024–2025.
May substitute for formal thesis, EAEE E9271, upon recommendation of the student's adviser.

EAEE E9271x and y–S9271 Earth and environmental engineering thesis
0–6 pts. Members of the faculty.
Research work culminating in a creditable dissertation on a problem of a fundamental nature selected in conference between student and adviser. Wide latitude is permitted in choice of a subject, but independent work of distinctly graduate character is required in its handling.

EAEE E9273x-E9274y Earth and environmental engineering reports
0–4 pts.
May substitute for the formal master's thesis, EAEE E9271, upon recommendation of the department.

EAEE E9280x and y Earth and environmental engineering colloquium
0 pts. Lect: 1.5. Professor Xu.
All graduate students are required to attend the departmental colloquium as long as they are in residence. Advanced doctoral students may be excused after three years of residence. No degree credit is granted.

EAEE E9302x and y Mining engineering research
0–4 pts. Not offered in 2024–2025.
Graduate research directed toward solution of technicoscientific problems in mining.

EAEE E9305x and y–S9305 Earth and environmental engineering research
0–12 pts. Members of the faculty.
Graduate research directed toward solution of a problem in mineral processing or chemical metallurgy.

EAEE E9800x and y–S9800 Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree in mineral engineering must register for 12 points of doctoral research instruction. Registration in EAEE E9800 may not be used to satisfy the minimum residence requirement for the degree.

EAEE E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the student's coursework has been completed, and until the dissertation has been accepted.

ELECTRICAL ENGINEERING

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Contemporary is a broad discipline that encompasses a wide range of activities. A common theme is the use of electrical and electromagnetic signals for the generation, transmission, processing, storage, conversion, and control of information and energy. An equally important aspect is the human interface and the role of individuals as the sources and recipients of information. The rates at which information is transmitted today range from megabits per second to gigabits per second and in some cases, as high as terabits per second. The range of frequencies over which these processes are studied extends from direct current (i.e., zero frequency), to microwave and optical frequencies.

The need for increasingly faster and more sophisticated methods of handling information poses a major challenge to the electrical engineer. New materials, devices, systems, and network concepts are needed to build the advanced communications and information handling systems of the future. Innovations in electrical engineering have had a dramatic impact on the way in which we work and live: the transistor, integrated circuits, computers, radio and television, satellite transmission systems, lasers, fiber optic transmission systems, and medical electronics.

The faculty of the Electrical Engineering Department at Columbia University is dedicated to the continued development of further innovations through its program of academic instruction and research. Our undergraduate program in electrical engineering is designed to prepare students for a career in industry, research, or business by providing them with a thorough foundation of the fundamental concepts and analytical tools of contemporary electrical engineering. A wide range of elective courses permits the student to emphasize specific disciplines such as communications, devices, circuits, or signal processing.

Undergraduates have an opportunity to learn firsthand about current research activities by participating in a program of undergraduate research projects with the faculty.

A master's level program in electrical engineering permits graduate students to further specialize their knowledge and skills within a wide range of disciplines. For those who are interested in pursuing a career in teaching, research, or advanced development, our Ph.D. program offers the opportunity to conduct research under faculty supervision at the leading edge of technology and applied science. Seminars are offered in all research areas.

The Electrical Engineering Department, along with the Computer Science Department, also offers B.S. and M.S. programs in computer engineering. Details on those programs can be found in the Computer Engineering section in this bulletin.

Research Activities

The research interests of the faculty encompass a number of rapidly growing areas, vital to the development of future technology, that will affect almost every aspect of society: signals, information, and data; networking and communications; nanoscale structures and integrated solid-state devices; nanoelectronics and nanophotonics; integrated circuits and systems; systems biology; neuroengineering; and smart electric energy. Details on all of these areas can be found at ee.columbia.edu/research.

The Signals, Information and Data area concerns the representation, processing, analysis, and communication of information embedded in signals and datasets arising in a wide range of application areas, including audio, video, images, communications, and biology. Research interests include the development of models, algorithms and analyses for sensing, detection and estimation, statistical and machine learning, and the recognition, organization, and understanding of the information content of signals and data.

The Networking and Communications area focuses on the design and performance evaluation of communication systems and data networks of all kinds, including wireless/cellular, optical, ultra-low power, vehicular, mobile, wearable, data center networks, cyber physical systems, and the internet. Methods range from analyzing and refining existing approaches to the development of new and evolving networking techniques and systems.

The Systems Biology and Neuroengineering area aims to understand and analyze biological systems within the living cell and in the brain. Examples of related tasks are biomolecular data analysis for medical applications, synthetic biology, establishing the principles of neuroinformation processing in the brain for developing robust sensory processing and motor control algorithms, accelerating the clinical translation of devices that make contact with neurons, and building massively parallel brain-computer interfaces.

The Integrated Circuits and Systems area focuses on the integration of circuits and systems on semiconductor platforms. Research spans the analysis, design, simulation, and validation of analog, mixed-mode, (sub) mm-wave, RF, power, and digital circuits, and their applications from computation and sensing to cyber-physical and implantable biomedical systems.

The area of Nanoscale Structures and Integrated Devices applies fundamental physical principles to develop revolutionary new electronic, photonic, and optical devices made from conventional and emerging materials, including graphene, 2D semiconductors, and organic semiconductors. Research includes nanofabrication, characterization, and electromagnetic design of quantum device structures and complex silicon photonic circuits that impact numerous fields from Lidar and optogenetics to low-energy computation and flexible electronics.

The smart electric energy area focuses on the optimization of the generation, conversion, distribution, and consumption of electric energy as well as the electrification of energy systems. Research spans the analysis, design, and control of power electronics, motor drive, and energy storage systems, grid resilience and security, and Internet-of-Things. Applications include transportation electrification, smart grid, renewable energy, and smart building systems.

Laboratory Facilities

Current research activities are fully supported by more than a dozen well-equipped research laboratories run by the department faculty. In addition, faculty and students have access to a clean room for micro- and nanofabrication, a materials-characterization facility, and an electron-microscopy facility, managed by the Columbia Nano Initiative. Faculty laboratories include Digital Video and Multimedia Networking Laboratory, Wireless and Mobile Networking Laboratory, Network Algorithms Laboratory, Genomic Information Systems Laboratory, Structure-Function Imaging Laboratory, Neural Acoustic Processing Laboratory, Signal Processing and Communication Laboratory, Translational Neuroelectronics Laboratory, Bionet Laboratory, Molecular Beam Epitaxy Laboratory, Surface Analysis Laboratory, Laboratory for Unconventional Electronics, Advanced Semiconductor Device Laboratory, Motor Drives and Power Electronics Laboratory, Intelligent and Connected Systems Laboratory, Columbia Integrated Systems Laboratory (CISL), Analog & RF IC Design Laboratory, VLSI Design Laboratory, High Speed and mmWave IC Laboratory, Analog and Mixed Signal IC Laboratory, Bioelectronics Laboratory, Lightwave Laboratory, and Nano Photonics Laboratory.

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

UNDERGRADUATE PROGRAM

The educational objective of the Electrical Engineering program, in support of the mission of the School, is to prepare graduates to achieve success in one or more of the following within a few years after graduation:

1. Graduate or professional studies—as evidenced by admission to a top-tier program, attainment of advanced degrees, research contributions, or professional recognition.
2. Engineering practice—as evidenced by entrepreneurship; employment in industry, government, academia, or nonprofit organizations in engineering; patents; or professional recognition.
3. Careers outside of engineering that take advantage of an engineering education—as evidenced by contributions appropriate to the chosen field.

The Electrical Engineering program will prepare its undergraduates to attain the following:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and

ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
EARLY-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester	
				and APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	UN1401 (3) → UN1601 (3.5) → UN2801 (4.5) →	UN1402 (3) UN1602 (3.5) UN2802 (4.5)		
CHEMISTRY	one-semester lecture (3–4) UN1403 **or** UN1404 **or** UN2045 **or** UN1604			
CORE REQUIRED COURSES	ELEN E1201 (3.5) Introduction to electrical engineering (either semester)		ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	ELEN E3331 (3) Electronic circuits CSEE W3827 (3) Fund. of computer sys.
REQUIRED LABS			ELEN E3081 (1)[2] Circuit analysis lab ELEN E3084 (1)[2] Signals and systems lab	ELEN E3083 (1)[2] Electronic circuits lab ELEN E3082 (1)[2] Digital systems lab
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES	HUMA CC1001, COCI CC1101, **or** Global Core (3–4); HUMA UN1121 **or** UN1123 (3); HUMA CC1002, COCI CC1102, **or** Global Core (3–4); ECON UN1105 (4) **and** UN1155 recitation (0); some of these courses can be postponed to the junior or senior year, to make room for taking the above electrical engineering courses.			
COMPUTER SCIENCE	ENGI E1006 (3) either semester[3]			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010.

[2] If possible, these labs should be taken along with their corresponding lecture courses.

[3] ENGI E1006 may not be offered every semester. See ee.columbia.edu for more discussion about the Computer Science sequences.

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

ELECTRICAL ENGINEERING: THIRD AND FOURTH YEARS
EARLY-STARTING STUDENTS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
PHYSICS (tracks continued)		UN1403 (3) → UN2601 (3.5) Lab UN3081 (2)	Lab UN1494 (3)[1]		
EE CORE REQUIRED COURSES		ELEN E3106 (3.5) Solid-state devices and materials	ELEN E3401 (4) Electromagnetics ELEN E3701 (3)[2] Intro. to communication systems **or** CSEE W4119 (3)[2] Computer networks		
EE REQUIRED LABS				ELEN E3043 (3) Solid state, microwave, and fiber optics lab ELEN E3399 (1) EE practice	ELEN E3390 (3)[3] Capstone design course
OTHER REQUIRED COURSES		IEOR E3658 **or** STAT GU4203[4]; **and** COMS W3136 (**or** W3134 or W3137)[5] (some of these courses *are not* offered both semesters. Students with an adequate background can take some of these courses in the sophomore year)			
ELECTIVES	**EE DEPTH TECH**	At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking (for details, see ee.columbia.edu)			
	BREADTH TECH	(at least 6 points total) At least two technical electives outside the chosen depth area; must be courses with significant engineering content (see ee.columbia.edu)			
	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[6]			
	NONTECH	Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement)			
TOTAL POINTS[7]		16.5	17	16	18

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[1] Chemistry lab (CHEM UN1500) may be substituted for physics lab, although this is not generally recommended.

[2] These courses can be taken in the sophomore year if the prerequisites/corequisites are satisfied.

[3] The capstone design course provides ELEN majors with a "culminating design experience." As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.

[4] SIEO W3600 and STAT GU4001 cannot generally be used to replace IEOR E3658 or STAT GU4203.

[5] Students who plan to minor in Computer Science should choose COMS W3134 or W3137.

[6] The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can also apply for this waiver, but the courses must have been at an advanced level for this to be considered.

[7] "Total points" assumes that 20 points of nontechnical electives and other courses are included.

ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
LATE-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101(3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester	
				and APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	UN1403 (3) UN2601 (3.5) Lab UN3081 (2)	Lab UN1494 (3)[2]
CHEMISTRY	one-semester lecture (3–4) UN1403 **or** UN1404 **or** UN2045 **or** UN1604			
ELECTRICAL ENGINEERING	ELEN E1201 (3.5) either semester[3]			
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
COMPUTER SCIENCE	ENGI E1006 (3) any semester[4]			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (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 either APMA E3101 or MATH UN2010.

[2] Chemistry lab (CHEM UN1500) may be substituted for physics lab, although this is not generally recommended.

[3] Transfer students and 3-2 Combined Plan students who have not taken ELEN E1201 prior to the junior year are expected to have taken a roughly equivalent course when they start ELEN E3201.

[4] ENGI E1006 may not be offered every semester. See ee.columbia.edu for more discussion about the Computer Science sequences.

practice. Graduates should be qualified to enter the profession of engineering, to continue toward a career in engineering research, or to enter other fields in which engineering knowledge is essential. Required nontechnical courses cover civilization and culture, philosophy, economics, and a number of additional electives. English communication skills are an important aspect of these courses. Required science courses cover basic chemistry and physics, whereas math requirements cover calculus, differential equations, probability, and linear algebra. Basic computer knowledge is also included, with an introductory course on using engineering workstations and two rigorous introductory computer science courses. Core electrical engineering courses cover the main components of modern electrical engineering and illustrate basic engineering principles. Topics include a sequence of two courses on circuit theory and electronic circuits, one course on semiconductor devices, one on electromagnetics, one on signals and systems, one on digital systems, and one on communications or networking. Engineering practice is developed further through a sequence of laboratory courses, starting with a first-year course to introduce hands-on experience early and to motivate theoretical work. Simple creative design experiences start immediately in this first-year course. Following this is a sequence of lab courses that parallel the core lecture courses. Opportunities for exploring design can be found both within these lab courses and

ELECTRICAL ENGINEERING: THIRD AND FOURTH YEARS
LATE-STARTING STUDENTS

		SEMESTER V	**SEMESTER VI**	**SEMESTER VII**	**SEMESTER VIII**
EE CORE REQUIRED COURSES		ELEN E3106 (3.5) Solid-state devices and materials ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	CSEE W3827(3) Fund. of computer sys. ELEN E3331 (3) Electronic circuits ELEN E3401 (4) Electromagnetics ELEN E3701 (3) Intro. to communication systems **or** CSEE W4119 (3) Computer networks		
EE REQUIRED LABS		ELEN E3081 (1)[1] Circuit analysis lab ELEN E3084 (1)[1] Signals and systems lab	ELEN E3083 (1)[1] Electronic circuits lab ELEN E3082 (1)[1] Digital systems lab	ELEN E3043 (3) Solid state, microwave, and fiber optics lab ELEN E3399 (1) EE practice	ELEN E3390 (3)[2] Capstone design course
OTHER REQUIRED COURSES		IEOR E3658 **or** STAT GU4203[3]; **and** COMS W3136 (**or** W3134 or W3137)[4] (Some of these courses are *not* offered both semesters)			
ELECTIVES	**EE DEPTH TECH**	At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. (For details, see ee.columbia.edu.)			
	BREADTH TECH	(at least 6 points total) At least two technical electives outside the chosen depth area; must be courses with significant engineering content (see ee.columbia.edu)			
	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[5]			
	NONTECH	Complete 27-point requirement; see page 9 (27-Point Nontechnical Requirement)			
TOTAL POINTS[6]		15.5	18	16	18

Note: This chart shows one possible schedule for a student who takes most of their major program in the final two years. Please refer to the previous chart for a recommended earlier start.

[1] If possible, these labs should be taken along with their corresponding lecture courses.

[2] The capstone design course provides ELEN majors with a “culminating design experience.” As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.

[3] SIEO W3600 and STAT GU4001 cannot generally be used to replace IEOR E3658 or STAT GU4203.

[4] Students who plan to minor in Computer Science should choose COMS W3134 or W3137.

[5] The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH UN2030 (formerly MATH E1210) and either APMA E3101 or MATH UN2010. Combined-plan students with good grades in separate, advanced courses in linear algebra and ODEs can also apply for this waiver, but the courses must have been at an advanced level for this to be considered.

[6] “Total points” assumes that 9 points of nontechnical electives are included.

in the parallel lecture courses, often coupled with experimentation and computer simulation, respectively. The culmination of the laboratory sequence and the design experiences introduced throughout earlier courses is a senior design course (capstone design course), which includes a significant design project that ties together the core program, encourages creativity, explores practical aspects of engineering practice, and provides additional experience with communication skills in an engineering context. Finally, several technical electives are required, chosen to provide both breadth and depth in a specific area of interest. More detailed program objectives and outcomes are posted at ee.columbia.edu.

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

There is a strong interaction between the Department of Electrical Engineering and the Departments of Computer Science, Applied Physics and Applied Mathematics, Industrial Engineering and Operations Research, Physics, and Chemistry.

EE Core Curriculum

All electrical engineering (EE) students must take a set of core courses, which collectively provide the student with fundamental skills, expose them to the breadth of EE, and serve as a springboard for more advanced work, or for work in areas not covered in the core. These courses are shown on the charts in Undergraduate Degree Tracks. A full curriculum checklist is also posted at ee.columbia.edu.

Technical Electives

The 18-point technical elective requirement for the electrical engineering program consists of three components: depth, breadth, and other. A general outline is provided here, and more specific course restrictions can be found at ee.columbia.edu. For any course not clearly listed there, adviser approval is necessary.

The *depth* component must consist of at least 6 points of electrical engineering courses in one of four defined areas: (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. The depth requirement provides an opportunity to pursue particular interests and exposure to the process of exploring a discipline in depth—an essential process that can be applied later to other disciplines, if desired.

The *breadth* component must consist of at least 6 additional points of courses that are outside of the chosen depth area and have significant engineering content. These courses can be from other departments within the School. The breadth requirement precludes overspecialization. Breadth is particularly important today, as innovation requires more and more of an interdisciplinary approach, and exposure to other fields is known to help one's creativity in one's own main field. Breadth also reduces the chance of obsolescence as technology changes.

Any remaining technical elective courses, beyond the minimum 12 points of depth and breadth, do not have to be engineering courses (except for students without *ELEN E1201* or approved transfer credit for *ELEN E1201*) but must be technical. Generally, math and science courses that do not overlap with courses used to fill other requirements are allowed.

If another department advertises that one of their courses can be used as a technical elective, that does not necessarily mean it will be approved as a technical elective in the electrical engineering program. Which courses are approved depends on other electives chosen due to the depth and breadth restrictions, and the need for sufficient engineering and technical content within the entire 18 points. Electrical engineering technical electives must also be 3000 level or above and must not have significant overlap with other courses taken for the major.

Starting Early

The EE curriculum is designed to allow students to start their study of EE in their first year. This motivates students early and allows them to spread nontechnical requirements more evenly. It also makes evident the need for advanced math and physics concepts, and motivates the study of such concepts. Finally, it allows more time for students to take classes in a chosen depth area, or gives them more time to explore before choosing a depth area. Students can start with *ELEN E1201: Introduction to electrical engineering* in the second semester of their first year, and can continue with other core courses one semester after that, as shown in the "early-starting students" chart. It is emphasized that both the early- and late-starting sample programs shown in the charts are examples only; schedules may vary depending on student preparation and interests.

Transfer Students

Transfer students coming to Columbia as juniors with sufficient general background can complete all requirements for the B.S. degree in electrical engineering. Such students fall into one of two categories:

Plan 1: Students coming to Columbia without having taken the equivalent of *ELEN E1201* must take this course in their junior year. This requires postponing the core courses in circuits and electronics until the senior year, and thus does not allow taking electives in that area; thus, such students cannot choose circuits and electronics as a depth area.

Plan 2: This plan is for students who have taken a course equivalent to *ELEN E1201* at their school of origin, including a laboratory component. See the bulletin for a description of this course. Many pre-engineering programs and physics departments at four-year colleges offer such courses. Such students can start taking circuits at Columbia immediately, and thus can choose circuits and electronics as a depth area.

It is stressed that *ELEN E1201* or its equivalent is a key part of the EE curriculum. The preparation provided by this course is essential for a number of other core courses.

Sample programs for both Plan 1 and Plan 2 transfer students can be found at ee.columbia.edu.

B.S./M.S. Program

The B.S./M.S. degree program is open to a select group of undergraduate students. This double degree program makes possible the earning of both the Bachelor of Science and Master of Science degrees in an integrated fashion. Up to 6 points may be credited to both degrees, and some graduate classes taken in the senior year may count toward the M.S. degree. Interested students can find further information at ee.columbia.edu and can discuss options directly with their faculty adviser. Students must be admitted prior to the start of their seventh semester at Columbia Engineering. Students in the 3-2 Combined Plan undergraduate program are not eligible for admission to this program.

GRADUATE PROGRAMS

The Department of Electrical Engineering offers graduate programs leading to the degree of Master of Science (M.S.) and the degrees of Doctor of Engineering Science (Eng.Sc.D.) and Doctor of Philosophy (Ph.D.). The Graduate Record Examination (General Test only) is required of all applicants except special students. An undergraduate grade-point average equivalent to B or better from an institution comparable to Columbia is expected.

Applicants who, for good reasons, are unable to submit GRE test results by the deadline date but whose undergraduate record is clearly superior may file an application without the GRE scores. An explanatory note should be added to ensure that the application will be processed even while incomplete. If the candidate's admissibility is clear, the decision may be made without the GRE scores; otherwise, it may be deferred until the scores are received.

There are no prescribed course requirements in any of the regular graduate degree programs. Students, in consultation with their faculty advisers, design their own programs, focusing on particular fields of electrical engineering. Among the fields of graduate study are Communications, Networking, Internet and Internet of Things; Computer Engineering; Integrated Circuits and Systems and Electronics; Integrated Devices and Photonics; Signals, Information, Data, Learning and Control; Smart Electric Energy; and Systems Biology and Neuroengineering.

Graduate course charts for several focus areas can be found at ee.columbia.edu.

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

Master of Science Degree

Candidates for the M.S. degree in electrical engineering must complete 30 points of credit beyond the bachelor's degree. A minimum of 15 points of credit must be at the 6000 level or higher. No credit will be allowed for undergraduate courses (3000 or lower). At least 15 points must be in electrical engineering, defined as including all courses with an ELEN designator or a joint designator containing electrical engineering as a member, e.g., EECS, CSEE, EEME, ECBM, etc. And it is expected that at least 12 of the first 24 points taken will be in electrical engineering.

Not all technical courses can be applied toward the M.S. degree, and some have restrictions. Up to 6 points of research (such as ELEN E4998, ELEN E6001, and ELEN E6002) can be applied. Up to 1.5 points of fieldwork (ELEN E6999) can be used. No more than 3 points of courses that do not contain primarily engineering, math, or science content can be used, subject to the written pre-approval of the department. Any course that is not on the list of standard courses specified at ee.columbia.edu/masters-program requires prior written department approval, including during the summer session.

The general school requirements listed earlier in this bulletin, such as minimum GPA, must also be satisfied. All degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

More details and a requirements checklist for approvals can be found at ee.columbia.edu/masters-program.

Doctoral Degree

The requirements for the Ph.D. and Eng.Sc.D. degrees are identical. Both require a dissertation based on the candidate's original research, conducted under the supervision of a faculty member. The work may be theoretical or experimental or both.

Students who wish to become candidates for the doctoral degree in electrical engineering have the option of applying for admission to the Eng.Sc.D. program or the Ph.D. program. Students who elect the Eng.Sc.D. degree register in the School of Engineering and Applied Science; those who elect the Ph.D. degree register in the Graduate School of Arts and Sciences.

Doctoral candidates must obtain a minimum of 60 points of formal course credit beyond the bachelor's degree. A master's degree from an accredited institution may be accepted as equivalent to 30 points. A minimum of 30 points beyond the master's degree must be earned while in residence in the doctoral program.

More detailed information regarding the requirements for the doctoral degree may be obtained in the department office and at ee.columbia.edu.

Optional M.S. Specializations

Students in the electrical engineering M.S. program often choose to use some of their electives to focus on a particular field. Students may pick one of a number of optional, formal specialization templates or design their own M.S. program in consultation with an adviser. These specializations are not degree requirements. They represent suggestions from the faculty as to how one might fill one's programs so as to focus on a particular area of interest. Students may wish to follow these suggestions, but they need not. The degree requirements are quite flexible and are listed in the Master of Science Degree section, above. All students, whether following a formal specialization template or not, are expected to include breadth in their program. Not all of the elective courses listed here are offered every year. For the latest information on available courses, visit the Electrical Engineering home page at ee.columbia.edu.

Specialization in Data-Driven Analysis and Computation

Advisers: Professors Dimitris Anastassiou, Shih-Fu Chang, Pedrag Jelenkovic, Zoran Kostic, Aurel A. Lazar, Nima Mesgarani, John Paisley, John Wright, Xiaofan (Fred) Jiang

1. Satisfy M.S. degree requirements.
2. Take at least two courses from *ECBM E4040: Neural networks and deep learning; EECS E4764: Internet of things—intelligent and connected systems; ELEN E4810: Digital signal processing; ELEN E4720: Machine learning for signals, information, and data; EEOR E6616: Convex optimization; EECS E6893: Topic: big data analytics.*
3. Take at least one courses from *ECBM E6040: Neural networks and deep learning research; EECS E6720: Bayesian models for machine learning; EECS E6765: Internet of things—systems and physical data analytics; EECS E6895: Topic: advanced big data analytics.*
4. Take a second course from #3 or one course from *ECBM E4060: Introduction to genomic information science and technology; ECBM E4070; ECBM: E607x: Topics in neuroscience and deep learning; EECS E6690: Topics in data-driven analysis and computation; ELEN E6876: Sparse and low-dimensional models for high-dimensional data; EECS E9601: Seminar in data-driven analysis and computation.*

Specialization in Networking

Advisers: Professors Predrag Jelenkovic, Javad Ghaderi, Ethan Katz-Bassett, Debasis Mitra, Gil Zussman, Xiaofan (Fred) Jiang

1. Satisfy M.S. degree requirements.
2. One basic networking course from the following*: ELEN E6761: Computer communication networks I, CSEE W4119: Computer networks.*
3. One basic systems or analytical course from the following: Systems courses: *CSEE W4140: Networking laboratory; COMS W4113: Fundamentals of large-scale distributed systems; COMS W4118: Operating systems I;* Analytical courses: *ELEN E6772: Topic: network algorithms; ELEN E6950: Wireless and mobile networking, I; CSEE E6180: Modeling and performance evaluation.*
4. Three courses from the following list (courses cannot be used to fulfill both this requirement and any of the above requirements): *ELEN E6488: Optical interconnects and interconnection networks; ELEN E6761: Computer communication networks I; ELEN E6767: internet economics, energy, and society; ELEN E6770: Topic: next generation networks; ELEN E6772: Topic: network algorithms; ELEN E6775: Topic: computer networks: a systems approach; ELEN E6776: Topic: content distribution networks; ELEN E6950: Wireless and mobile networking I; EEOR E4650: Convex optimization for EE; EEOR E6616: Convex optimization; CSEE W4140: Networking laboratory; EECS E4951: Wireless networks and systems; CSEE E6180: Modeling and Performance Evaluation; COMS W4180: Network security; COMS W4995: Internet technology, economics, and policy, COMS E6181: Advanced internet services; COMS E6998: Cloud computing and big data; IEOR E6704: Queueing theory; IEOR E4106: Stochastic models; with adviser approval, other relevant advanced topic courses on networking topics from ELEN E677x, COMS W4995, COMS E6998, or other course numbers may be used to fulfill this requirement.*
5. At least two of the four courses used to fulfill requirements 3 and 4 must be 6000-level ELEN, EECS, CSEE, or EEOR courses.

Specialization in Wireless and Mobile Communications

Advisers: Professors Gil Zussman, Predrag Jelenkovic, Xiaodong Wang

1. Satisfy M.S. degree requirements.
2. One basic circuits course such as: *ELEN E4312: Analog electric circuits; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6312: Advanced analog ICs.*
3. Two communications or networking courses such as: *CSEE W4119: Computer networks; ELEN E4702: Digital communications; ELEN E4703: Wireless communications; ELEN E6711: Stochastic signals and noise; ELEN E4810: Digital signal processing; ELEN E6950: Wireless and mobile networking, I; EECS E4951: Wireless network and systems; ELEN E6761: Computer communication networks, I; ELEN E6712: Communication theory; ELEN E6713: Topics in communications; ELEN E6717: Information theory; ELEN E677x: Topics in telecommunication networks.*
4. At least two additional approved courses in wireless communications or a related area.

Specialization in Integrated Circuits and Systems

Advisers: Professors Peter Kinget, Harish Krishnaswamy, Mingoo Seok, Kenneth Shepard, Yannis Tsividis, Charles Zukowski

1. Satisfy M.S. degree requirements.
2. One digital course from: *EECS E4321: Digital VLSI circuits* or *EECS E6321: Advanced digital electronic circuits.*
3. One analog course from *ELEN E4312: Analog electronic circuits; ELEN E6312: Advanced analog integrated circuits; ELEN E6316: Analog digital interfaces in VLSI; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6320: Millimeter-wave IC design.*
4. Two additional courses such as other courses from no. 2 and 3; *ELEN E6350: VLSI design laboratory; ELEN E6304: Topics in electronic circuits; ELEN E6318: Microwave circuit design; ELEN E9303: Seminar in electronic circuits.*
5. At least one additional approved course in integrated circuits and systems or a related area.

Specialization in Smart Electric Energy

Advisers: Professors Matthias Preindl, Xiaofan (Fred) Jiang, Gil Zussman, Kenneth Shepard, Xiaodong Wang

1. Satisfy M.S. degree requirements.
2. Take at least two power conversion or power systems courses from: *ELEN E4361: Power electronics; ELEN E6902 Renewable power systems; ELEN E6904: Motor drive systems; ELEN E4511: Power systems analysis and control; ELEN E4510: Solar energy and smart grid power systems.*
3. Take at least one control or optimization course from: *EEME E4601: Digital control systems; EEME E6601: Introduction to control theory; EEME E6602: Modern control theory; ELEN E6873: Statistical Signal Processing and Learning; EEOR E4650: Convex optimization for electrical engineering; EEOR E6616: Convex optimization; EECS E4764: IoT—intelligent and connected systems; CSEE W4840: Embedded system Design.*
4. Take at least one nonelectric energy class course from: *MECE E4210: Energy infrastructure planning; MECE E4320: Intro to combustion; MECE E4211: Energy: sources and conversions; MECE E4302: Advanced thermodynamics; EAEE E4190: Photovoltaic systems engineering and sustainability; EAEE E4257: Environmental data analysis and modeling; EAEE E4301: Carbon storage; EAEE E4302: Carbon capture; EAEE E4304: Closing the carbon cycle*.
5. Not required, but consider taking one of the following energy policy or market nontechnical elective courses (this course will fill the quota of nontechnical courses on the M.S. Checklist): *EAEE E4001: Industrial ecology of earth resources; EAIA W4200: Alternative energy resources; INAF U6057 Electricity markets; INAF U6072: Energy systems fundamentals; SUMA K4135: Energy analysis for energy efficiency; INAF U6065: The economics of energy; INAF U6061: Global energy policy; INAF U6242: Energy policy; INAF U6135: Renewable energy markets and policy.*

Specialization in Systems Biology and Neuroengineering

Advisers: Professors Dimitris Anastassiou, Christine Hendon, Pedrag Jelenkovic, Aurel A. Lazar, Nima Mesgarani, Kenneth Shepard, Xiaodong Wang

1. Satisfy M.S. degree requirements.
2. Take both *ECBM E4060: Introduction to genomic information science and technology* and *BMEB W4020: Computational neuroscience, circuits in the brain*
3. Take at least one course from *BMEE E4030: Neural control engineering; ECBM E4040: Neural networks and deep learning; ECBM E4070; ECBM E4090: Brain computer interfaces (BCI) laboratory; CBMF W4761: Computational genomics; ELEN E6010: Systems biology: design principles for biological circuits*; *EEBM E6020: Methods in computational neuroscience*; *BMEE E6030: Neural modeling and neuroengineering*.
4. Take at least one course from *ECBM E6040: Neural networks and deep learning research; ECBM E607x: Topics in neuroscience and deep learning; ELEN E608x: Topics in systems biology; EEBM E609x: Topics in computational neuroscience and neuroengineering; ELEN E6261: Computational methods of circuit analysis ELEN E6717: Information theory; ELEN E6860: Advanced digital signal processing.*

Specialization in Lightwave (Photonics) Engineering

Advisers: Professors Keren Bergman, Ioannis (John) Kymissis, Michal Lipson

1. Satisfy M.S. degree requirements.
2. Take both *ELEN E4411: Fundamentals of photonics* and *ELEN E6412: Lightware devices* (or an E&M course, such as *APPH E4300: Applied electrodynamics* or *PHYS GR6092: Electromagnetic theory*).
3. One more device/circuits/photonics course such as: *ELEN E6413: Lightwave systems; ELEN E6414: Photonic integrated circuits; ELEN E4314: Communication circuits; ELEN E4488: Optical systems; ELEN E6488: Optical interconnects and interconnection networks; ELEN E4193: Modern display science and technology.*
4. At least two additional approved courses in photonics or a related area. Options also include courses outside EE such as *APPH E4090: Nanotechnology; APPH E4100: Quantum physics of matter; APPH E4110: Modern optics; CHAP E4120: Statistical mechanics; APPH E4112: Laser physics; APPH E4130: Physics of solar energy; APPH E6081: Solid state physics, I; APPH E6082: Solid state physics, II; APPH E6091: Magnetism and magnetic materials; APPH E6110: Laser interactions with matter; MSAE E4202: Thermodynamics and reactions in solids; MSAE E4206: Electronic and magnetic properties of solids; MSAE E4207: Lattice vibrations and crystal defects; MSAE E6120: Grain boundaries and interfaces; MSAE E6220: Crystal physics; MSAE E6229: Energy and particle beam processing of materials; MSAE E6225: Techniques in X-ray and neutron diffraction.*

Specialization in Microelectronic Devices

Advisers: Professors Dion Khodagholy, Ioannis (John) Kymissis, Michal Lipson, James Teherani, Wen Wang

1. Satisfy M.S. degree requirements.
2. One basic course such as: *ELEN E4301: Introduction to semiconductor devices* or *ELEN E4411: Fundamentals of photonics.*
3. One advanced course such as: *ELEN E4193: Modern display science and technology; ELEN E4944: Principles of device microfabrication; ELEN E4503: Sensors, actuators, and electromechanical systems; ELEN E6151: Surface physics and analysis of electronic materials; ELEN E6331: Principles of semiconductor physics, I; ELEN E6332: Principles of semiconductor physics, II; ELEN E6333: Semiconductor device physics; ELEN E6945: Nanoscale fabrication and devices.*
4. At least two other approved courses in devices or a related area. Options also include courses outside EE such as *APPH E4090: Nanotechnology; APPH E4100: Quantum physics of matter; APPH E4110: Modern optics; CHAP E4120: Statistical mechanics;*

APPH E4112: Laser physics; APPH E4130: Physics of solar energy; APPH E6081: Solid state physics, I; APPH E6082: Solid state physics, II; APPH E6091: Magnetism and magnetic materials; APPH E6110: Laser interactions with matter; MSAE E4202: Thermodynamics and reactions in solids; MSAE E4206: Electronic and magnetic properties of solids; MSAE E4207: Lattice vibrations and crystal defects; MSAE E6120: Grain boundaries and interfaces; MSAE E6220: Crystal physics; MSAE E6229: Energy and particle beam processing of materials; MSAE E6225: Techniques in X-ray and neutron diffraction.

COURSES IN ELECTRICAL ENGINEERING

ELEN E1101x or y The digital information age
3 pts. Lect: 3. Professor Vallancourt.
An introduction to information transmission and storage, including technological issues. Binary numbers; elementary computer logic; digital speech and image coding; basics of compact disks, telephones, modems, faxes, UPC bar codes, and the World Wide Web. Projects include implementing simple digital logic systems and Web pages. Intended primarily for students outside the School of Engineering and Applied Science. The only prerequisite is a working knowledge of elementary algebra.

ELEN E1201x and y Introduction to electrical engineering
3.5 pts. Lect: 3. Lab: 1. Professor Vallancourt.
Prerequisite(s): MATH UN1101. Basic concepts of electrical engineering. Exploration of selected topics and their application. Electrical variables, circuit laws, nonlinear and linear elements, ideal and real sources, transducers, operational amplifiers in simple circuits, external behavior of diodes and transistors, first order RC and RL circuits. Digital representation of a signal, digital logic gates, flip-flops. A lab is an integral part of the course. Required of electrical engineering and computer engineering majors.

ELEN E3043x Solid state, microwave, and fiber optics laboratory
3 pts. Lect: 1. Lab: 6. Professor W. Wang.
Prerequisite(s): ELEN E3106 and ELEN E3401. Optical electronics and communications. Microwave circuits. Physical electronics.

ELEN E3081x Circuit analysis laboratory
1 pt. Lab: 3. Professor Zukowski.
Prerequisite(s): ELEN E1201 or equivalent. Corequisite(s): ELEN E3201. Companion lab course for ELEN E3201. Experiments cover such topics as: use of measurement instruments; HSPICE simulation; basic network theorems; linearization of nonlinear circuits using negative feedback; op-amp circuits; integrators; second order RLC circuits. The lab generally meets on alternate weeks.

ELEN E3082y Digital systems laboratory
1 pt. Lab: 3. Professor Shepard.
Corequisite(s): CSEE W3827. Recommended preparation: ELEN E1201 or equivalent. Companion lab course for CSEE W3827. Experiments cover such topics as logic gates; flip-flops; shift registers; counters; combinational logic circuits; sequential logic circuits; programmable logic devices. The lab generally meets on alternate weeks.

ELEN E3083y Electronic circuits laboratory
1 pt. Lab: 3. Professor Vallancourt.
Prerequisite(s): ELEN E3081. Corequisite(s): ELEN E3331. Companion lab course for ELEN E3331. Experiments cover such topics as macromodeling of nonidealities of opamps using SPICE; Schmitt triggers and astable multivibrations using opamps and diodes; logic inverters and amplifiers using bipolar junction transistors; logic inverters and ring oscillators using MOSFETs; filter design using opamps. The lab generally meets on alternate weeks.

ELEN E3084x Signals and systems laboratory
1 pt. Lab: 3. Professor X. Wang.
Corequisite(s): ELEN E3801. Companion lab course for ELEN E3801. Experiments cover topics such as: introduction and use of MATLAB for numerical and symbolic calculations; linearity and time invariance; continuous-time convolution; Fourier-series expansion and signal reconstruction; impulse response and transfer function; forced response. The lab generally meets on alternate weeks.

ELEN E3106x Solid-state devices and materials
3.5 pts. Lect: 3. Recit: 1. Professor Kymissis.
Prerequisite(s): MATH UN1201 or APMA E2000 or equivalent. Corequisite(s): PHYS UN1403 or PHYS UN2601 or equivalent. Crystal structure and energy band theory of solids. Carrier concentration and transport in semiconductors. P-n junction and junction transistors. Semiconductor surface and MOS transistors. Optical effects and optoelectronic devices. Fabrication of devices and the effect of process variation and distribution statistics on device and circuit performance.

ELEN E3201x Circuit analysis
3.5 pts. Lect: 3. Recit: 1. Professor Zukowski.
Prerequisite(s): ELEN E1201 or equivalent. Corequisite(s): MATH UN1201 or APMA E2000. A course on analysis of linear and nonlinear circuits and their applications. Formulation of circuit equations. Network theorems. Transient response of first and second order circuits. Sinusoidal steady state-analysis. Frequency response of linear circuits. Poles and zeros. Bode plots. Two-port networks.

ELEN E3331y Electronic circuits
3 pts. Lect: 3. Professor Zukowski.
Prerequisite(s): ELEN E3201. Operational amplifier circuits. Diodes and diode circuits. MOS and bipolar junction transistors. Biasing techniques. Small-signal models. Single-stage transistor amplifiers. Analysis and design of CMOS logic gates. A/D and D/A converters.

ELEN E3390y Electrical engineering senior design project
3 pts. Lab: 6. Professor Vallancourt.
Prerequisite(s): ELEN E3399 and completion of most other required EE courses. Students work in teams to specify, design, implement and test an engineering prototype. Involves technical as well as non-technical considerations, such as manufacturability, impact on the environment, economics, adherence to engineering standards, and other real-world constraints. Projects are presented publicly by each design team in a school-wide expo.

ELEN E3399x Electrical engineering practice
1 pt. Professor Vallancourt.
Design project planning, written and oral technical communication, the origin and role of standards, engineering ethics, and practical aspects of engineering as a profession, such as career development and societal and environmental impact. Generally taken senior year just before ELEN E3390.

ELEN E3401y Electromagnetics
4 pts. Lect: 3. Professor Bergman.
Prerequisite(s): MATH UN1201 or APMA E2000, PHYS UN1402 or PHYS UN1602, or equivalents. Basic field concepts. Interaction of time-varying electromagnetic fields. Field calculation of lumped circuit parameters. Transition from electrostatic to quasistatic and electromagnetic regimes. Transmission lines. Energy transfer, dissipation, and storage. Waveguides. Radiation.

EEME E3601x Classical control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite(s): MATH UN2030. Analysis and design of feedback control systems. Transfer functions; block diagrams; proportional, rate, and integral controllers; hardware; implementation. Routh stability criterion, root locus, Bode and Nyquist plots, compensation techniques.

ELEN E3701y Introduction to communication systems
3 pts. Lect: 3. Professor Kalet.
Prerequisite(s): ELEN E3801. Corequisite(s): IEOR E3658. A basic course in communication theory, stressing modern digital communication systems. Nyquist sampling, PAM and PCM/DPCM systems, time division multiplexing, high frequency digital (ASK, OOK, FSK, PSK) systems, and AM and FM systems. An introduction to noise processes, detecting signals in the presence of noise, Shannon's theorem on channel capacity, and elements of coding theory.

ELEN E3801x Signals and systems
3.5 pts. Lect: 3. Professor X. Wang.
Corequisite(s): MATH UN1201 or APMA E2000. Modeling, description, and classification of signals and systems. Continuous-time systems. Time domain analysis, convolution. Frequency domain analysis, transfer functions. Fourier series. Fourier and Laplace transforms. Discrete-time systems

and the Z transform.

CSEE W3827x and y Fundamentals of computer systems
3 pts. Lect: 3. Professor Kim.
Prerequisite(s): An introductory programming course. Fundamentals of computer organization and digital logic. Boolean algebra, Karnaugh maps, basic gates and components, flip-flops and latches, counters and state machines, basics of combinational and sequential digital design. Assembly language, instruction sets, ALUs, single-cycle and multicycle processor design, introduction to pipelined processors, caches, and virtual memory.

ELEN E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Research training course. Recommended in preparation for laboratory-related research.

ELEN E3990x, y or s Fieldwork
1–2 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used for degree credit. Only for Electrical Engineering and Computer Engineering undergraduate students who include relevant off-campus work experience as part of their approved program of study. Final report and letter of evaluation required. May not be used as technical or nontechnical electives or to satisfy any other Electrical Engineering or Computer Engineering major requirements. May not be taken for pass/fail credit or audited.

ELEN E3998x and y Projects in electrical engineering
0 to 3 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

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

ECBM E4040x or y Neural networks and deep learning
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): BMEB W4020 or BMEE E4030 or ECBM E4090 or ELEN E4750 or COMS W4771 or an equivalent. Developing features and internal representations of the world, artificial neural networks, classifying handwritten digits with logistics regression, feedforward deep networks, back propagation in multilayer perceptrons, regularization of deep or distributed models, optimization for training deep models, convolutional neural networks, recurrent and recursive neural networks, deep learning in speech, and object recognition.

ECBM E4060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Cheng.
Introduction to computational biology with emphasis on genomic data science tools and methodologies for analyzing data, such as genomic sequences, gene expression measurements and the presence of mutations. Applications of machine learning and exploratory data analysis for predicting drug response and disease progression. Latest technologies related to genomic information, such as single-cell sequencing and CRISPR, and the contributions of genomic data science to the drug development process.

ECBM E4070y Computing with brain circuits of model organisms
3 pts. Lect: 3. Professor Lazar.
Prerequisite(s): ELEN E3801 or BIOL UN3004, and Python programming experience, or instructor's permission. Building the functional map of the fruit fly brain. Molecular transduction and spatio-temporal encoding in the early visual system. Predictive coding in the Drosophila retina. Canonical circuits in motion detection. Canonical navigation circuits in the central complex. Molecular transduction and combinatorial encoding in the early olfactory system. Predictive coding in the antennal lobe. The functional role of the mushroom body and the lateral horn. Canonical circuits for associative learning and innate memory. Projects in Python.

ECBM E4090x or y Brain computer interfaces (BCI) laboratory
3 pts. Lect: 2. Lab: 3. Professor Mesgarani.
Prerequisite(s): ELEN E3801. Hands-on experience with basic neural interface technologies. Recording EEG (electroencephalogram) signals using data acquisition systems (noninvasive, scalp recordings). Real-time analysis and monitoring of brain responses. Analysis of intention and perception of external visual and audio signals.

ELEN E4106x Advanced solid state devices and materials
3 pts. Lect: 2.5. Lab: 1. Professor Kymissis.
Prerequisite(s): APMA E2000 and Math UN1201. Corequisites: PHYS UN1403 and UN2601. Crystal structure and energy band theory of solids. Carrier concentration and transport in semiconductors. P-n junction and junction transistors. Semiconductor surface and MOS transistors. Optical effects and optoelectronic devices. Fabrication of devices and the effect of process variation and distribution statistics on device and circuit performance. Course shares lectures with ELEN E3106, but the work requirements differ. Undergraduate students are not eligible to register.

CSEE W4119x and y Computer networks
3 pts. Lect: 3. Professor Rubenstein.
Corequisite(s): IEOR E3658 or SIEO W3600 or equivalents. Introduction to computer networks and the technical foundations of the internet, including applications, protocols, local area networks, algorithms for routing and congestion control, security, elementary performance evaluation. Several written and programming assignments required.

CSEE W4121y Computer systems for data science
3 pts. Lect: 3. Professor Cidon.
Prerequisite(s): Background in Computer System Organization and good working knowledge of C/C++. Corequisite(s): CSOR W4246, STAT GU4203, or equivalent approved by faculty adviser. Introduction to computer distributed systems with emphasis on warehouse scale computing systems. Topics include fundamental tradeoffs in computer systems, hardware and software techniques for exploiting instruction-level parallelism, data-level parallelism and task level parallelism, scheduling, caching, prefetching, network and memory architecture, latency and throughput optimizations, specializations, and introduction to programming data center computers.

CSEE W4140x or y Networking laboratory
3 pts. Lect: 3. Professor Zussman.
Prerequisite(s): CSEE W4119 or equivalent. In this course, students learn how to put “principles into practice,” in a hands-on-networking lab course. The technologies and protocols of the internet are covered, using equipment currently available to large internet service providers such as CISCO routers and end-systems. A set of laboratory experiments provides hands-on experience with engineering wide-area networks and familiarizes students with the Internet Protocol (IP), Address Resolution Protocol (ARP), Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), the Domain Name System (DNS), routing protocols (RIP, OSPF, BGP), network management protocols (SNMP), and application-level protocols (FTP, TELNET, SMTP).

ELEN E4193x or y Modern display science and technology
3 pts. Lect: 3. Professor Kymissis.
Prerequisite(s): Linear algebra, differential equations, and basic semiconductor physics. Introduction to modern display systems in an engineering context. The basis for visual perception, image representation, color space, metrics of illumination. Physics of luminescence, propagation and manipulation of light in anisotropic media, emissive displays, and spatial light modulators. Fundamentals of display addressing, the Alt-Pleshko theorem, multiple line addressing. Large area electronics, fabrication,

and device integration of commercially important display types. A series of short laboratories will reinforce material from the lectures. Enrollment may be limited.

EEEL E4220x Energy system economics and optimization
3 pts. Lect: 3. Professor Xu.
Prerequisite(s): Basic linear algebra, basic probability and statistics, and basic programming skills. Fundamental of power system economics over which the current electricity markets are designed. Formulation of unit commitment and economic dispatch as mathematical optimization. Modeling of thermal generators, renewable generators, energy storage, and other grid resources in power system optimization. Introduction of equilibriums in electricity markets. Introduction of ancillary service markets. Overview of current energy system research topics. Designed for master's and doctoral students, but is also open to undergraduates with the appropriate foundation classes.

ELEN E4312x Analog electronic circuits
3 pts. Lect: 3. Professor Dickson.
Prerequisite(s): ELEN E3331 and E3801. Differential and multistage amplifiers; small-signal analysis; biasing techniques; frequency response; negative feedback; stability criteria; frequency compensation techniques. Analog layout techniques. An extensive design project is an integral part of the course.

ELEN E4314y Communication circuits
3 pts. Lect: 3. Professor Tsividis.
Prerequisite(s): ELEN E4312. Principles of electronic circuits used in the generation, transmission, and reception of signal waveforms, as used in analog and digital communication systems. Nonlinearity and distortion; power amplifiers; tuned amplifiers; oscillators; multipliers and mixers; modulators and demodulators; phase-locked loops. An extensive design project is an integral part of the course.

EECS E4321x Digital VLSI circuits
3 pts. Lect: 3. Professor Shepard.
Recommended preparation: ELEN E3106, E3331, and CSEE W3827. Design and analysis of high speed logic and memory. Digital CMOS and BiCMOS device modeling. Integrated circuit fabrication and layout. Interconnect and parasitic elements. Static and dynamic techniques. Worst-case design. Heat removal and I/O. Yield and circuit reliability. Logic gates, pass logic, latches, PLAs, ROMs, RAMs, receivers, drivers, repeaters, sense amplifiers.

EECS E4340x Computer hardware design
3 pts. Lect: 2. Lab: 3. Professor Sethumadhavan.
Prerequisite(s): ELEN E3331 and CSEE W3827. Practical aspects of computer hardware design through the implementation, simulation, and prototyping of a PDP-8 processor. High-level and assembly languages, I/O, interrupts, datapath and control design, pipelining, busses, memory architecture. Programmable logic and hardware prototyping with FPGAs. Fundamentals of VHDL for register-transfer level design. Testing and validation of hardware. Hands-on use of industry CAD tools for simulation and synthesis.

ELEN E4361x or y Power electronics
3 pts. Lect: 3. Professor Preindl.
Prerequisite(s): ELEN E3801 and E3331. Introduction to power electronics; power semiconductor devices: power diodes, thyristors, commutation techniques, power transistors, power MOSFETs, Triac, IGBTs, etc., and switch selection; nonsinusoidal power definitions and computations, modeling, and simulation; half-wave rectifiers; single-phase, full-wave rectifiers; three-phase rectifiers; AC voltage controllers; DC/DC buck, boost, and buck-boost converters; discontinuous conduction mode of operation; DC power supplies: flyback, forward converter; DC/AC inverters, PWM techniques; three-phase inverters.

ELEN E4411x Fundamentals of photonics
3 pts. Lect: 3. Professor Lipson.
Prerequisite(s): ELEN E3401 or equivalent. Planar resonators. Photons and photon streams. Photons and atoms: energy levels and band structure; interactions of photons with matter; absorption, stimulated and spontaneous emission; thermal light, luminescence light. Laser amplifiers: gain, saturation, and phase shift; rate equations; pumping. Lasers: theory of oscillation; laser output characteristics. Photons in semiconductors: generation, recombination, and injection; heterostructures; absorption and gain coefficients. Semiconductor photon sources: LEDs; semiconductor optical amplifiers; homojunction and heterojunction laser diodes. Semiconductor photon detectors: p-n, p-i-n, and heterostructure photodiodes; avalanche photodiodes.

ELEN E4488x Optical systems
3 pts. Lect: 3. Professor Hendon.
Prerequisite(s): ELEN E3401 or equivalent. Introduction to optical systems based on physical design and engineering principles. Fundamental geometrical and wave optics with specific emphasis on developing analytical and numerical tools used in optical engineering design. Focus on applications that employ optical systems and networks, including examples in holographic imaging, tomography, Fourier imaging, confocal microscopy, optical signal processing, fiber optic communication systems, optical interconnects and networks.

ELEN E4511x or y Power systems analysis and control
3 pts. Lect: 3.
Prerequisite(s): ELEN E3201 and E3401, or equivalents, or instructor's permission. Modeling of power networks, steady-state and transient behaviors, control and optimization, electricity market, and smart grid.

EEME E4601y Digital control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite(s): ELEN E3801 or EEME E3601, or equivalent. Real-time control using digital computers. Solving scalar and state-space difference equations. Discrete equivalents of continuous systems fed by holds. Z-transfer functions. Creating closed-loop difference equation models by Z-transform and state variable approaches. The Nyquist frequency and sample rate selection. Classical- and modern-based digital control laws. Digital system identification.

ELEnf E4620y Numerical methods for data analysis
3 pts. Lect: 3. Professor Anderson
Prerequisite(s): Basic linear algebra and ability to write simple scripts in Matlab or Python. An introduction to the mathematical and computational foundations of data analysis with linear models. Develops theoretical and computational understanding of numerical linear algebra algorithms for problems including data fitting, data classification, clustering, and data reduction. Focus includes vector spaces, matrix factorization, least squares methods, and singular value decompositions. Illustrations on a variety of engineering applications, including power networks, autonomous and electric vehicles, quantum computing, medical imaging, and systems biology.

EEOR E4650x or y Convex optimization for electrical engineering
3 pts. Lect: 3.
Prerequisite(s): ELEN E3801 or instructor's permission. Theory of convex optimization; numerical algorithms; applications in circuits, communications, control, signal processing and power systems.

ELEN E4702x or y Digital communications
3 pts. Lect: 3. Professor Raghavan.
Prerequisite(s): ELEN E3701 or equivalent. Digital communications for both point-to-point and switched applications is further developed. Optimum receiver structures and transmitter signal shaping for both binary and M-ary signal transmission. An introduction to block codes and convolutional codes, with application to space communications.

ELEN E4703y Wireless communications
3 pts. Lect: 3. Professor Samardzia.
Prerequisite(s): ELEN E3701 or equivalent. Wireless communication systems. System design fundamentals. Trunking theory. Mobile radio propagation. Reflection of radio waves. Fading and multipath. Modulation techniques; signal space; probability of error, spread spectrum. Diversity. Multiple access.

ELEN E4720x or y Machine learning for signals, information, and data
3 pts. Lect: 3. Professor Paisley.
Prerequisite(s): Basic linear algebra and calculus. Intro-level courses in probability and statistics. Programming. Introduction to supervised and unsupervised techniques for machine learning. Probabilistic and non-probabilistic approaches. Focus on classification and regression models, clustering methods, matrix factorization and sequential models. Linear and logistic regression, support vector machines, boosting, K-means clustering, mixture models, expectation-maximization algorithm, and hidden Markov models. Algorithmic techniques for optimization, such as gradient and coordinate descent methods.

ELEN E4730y Quantum Optimization and Machine Learning
3 pts. Lect: 3. Professor X. Wang.
Prerequisite(s): Probability theory, linear algebra. An introduction to the recent development in quantum optimization and quantum machine learning using gate-based Noisy Intermediate Scale Quantum (NISQ) computers. IBM's quantum programming framework Qiskit is utilized. Qbits, quantum gates and quantum measurements, quantum algorithms (Grover's search, Simon's algorithm, quantum Fourier transform, quantum phase estimation) quantum optimization (quantum annealing, QAOA, variational quantum eigensolver), quantum machine learning (quantum support vector machine, quantum neural networks).

BMEE E4740y Bioinstrumentation
3 pts. Lect: 1. Lab: 3. Professor Kyle.
Prerequisite(s): COMS W1005, ELEN E1201. Hands-on experience designing, building, and testing the various components of a benchtop cardiac pacemaker. Design instrumentation to measure biomedical signals as well as to actuate living tissues. Transducers, signal conditioning electronics, data acquisition boards, the Arduino microprocessor, and data acquisition and processing using MATLAB will be covered. Various devices will be discussed throughout the course, with laboratory work focusing on building an emulated version of a cardiac pacemaker. Lab required.

EECS E4750x or y Heterogeneous computing for signal and data processing
3 pts. Lect: 2. Professor Marianetti.
Prerequisite(s): ELEN E3801 and COMS W3134 or similar, recommended. Methods for deploying signal and data processing algorithms on contemporary general purpose graphics processing units (GPGPUs) and heterogeneous computing infrastructures. Using programming languages such as OpenCL and CUDA for computational speedup in audio, image, and video processing and computational data analysis. Significant design project.

EECS E4764 Internet of things—intelligent and connected systems
3 pts. Lect 3. Professor Jiang.
Prerequisite(s): Knowledge of programming or instructor's permission. Recommended: ELEN E4703, CSEE W4119, CSEE W4840, or related courses. Cyber-physical systems and Internet of Things. Various sensors and actuators, communication with devices through serial protocols and buses, embedded hardware, wired and wireless networks, embedded platforms such as Arduino and smartphones, web services on end devices and in the cloud, visualization and analytics on sensor data, end-to-end IoT applications. Group projects to create working CPS/IoT system.

EECS E4766 Internet of things—engineering innovations and commercialization
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): Basic programming and instructor's permission. Deep dive into a couple of selected topics/use-cases from the area of Internet of Things. Coverage of the topic from device to the cloud, with focus on practical aspects. Innovative product definition, product development, marketing, commercialization, and monetization. Cross-disciplinary coverage: EE, MechE, CS, Bioengineering, marketing, business, design. Building products and startups in the IoT domain. Collaboration between the Engineering School, Business School, industry experts, and engagement in IoT activities in NYC. Collaborative project by groups of students from different disciplines. This course shares lectures with E6766, but the expected project complexity is lower.

ELEN E4810x Digital signal processing
3 pts. Lect: 3. Professor Wright.
Prerequisite(s): ELEN E3801. Digital filtering in time and frequency domain, including properties of discrete-time signals and systems, sampling theory, transform analysis, system structures, IIR and FIR filter design techniques, the discrete Fourier transform, fast Fourier transforms.

ELEN E4815y Random signals and noise
3 pts. Lect: 3. Professor Kalet.
Prerequisite(s): IEOR E3658 or equivalent. Characterization of stochastic processes as models of signals and noise; stationarity, ergodicity, correlation functions, and power spectra. Gaussian processes as models of noise in linear and nonlinear systems; linear and nonlinear transformations of random processes; orthogonal series representations. Applications to circuits and devices, to communication, control, filtering, and prediction.

CSEE W4823x or y Advanced logic design
3 pts. Lect: 3.
Prerequisite(s): CSEE W3827 or equivalent. An introduction to modern digital system design. Advanced topics in digital logic: controller synthesis (Mealy and Moore machines); adders and multipliers; structured logic blocks (PLDs, PALs, ROMs); iterative circuits. Modern design methodology: register transfer level modeling (RTL); algorithmic state machines (ASMs); introduction to hardware description languages (VHDL or Verilog); system-level modeling and simulation; design examples.

CSEE W4824x or y Computer architecture
3 pts. Lect: 3. Professor Sethumadhavan.
Prerequisite(s): CSEE W3827 or equivalent. Focuses on advanced topics in modern computer architecture, illustrated by recent case studies. Fundamentals of quantitative analysis. Pipelined, out-of-order, and speculative execution. Superscalar, VLIW and vector processors. Embedded processors. Memory hierarchy design. Multiprocessors and thread-level parallelism. Synchronization and cache coherence protocols. Interconnection networks.

ELEN E4830y Digital image processing
3 pts. Lect: 3. Professor Hendon.
Introduction to the mathematical tools and algorithmic implementation for representation and processing of digital pictures, videos, and visual sensory data. Image representation, filtering, transform, quality enhancement, restoration, feature extraction, object segmentation, motion analysis, classification, and coding for data compression. A series of programming assignments reinforces material from the lectures.

ELEN E4835 Introduction to adaptive signal representations
3 pts. Lect: 2. Professor Wright.
Prerequisite(s): Linear algebra (APMA E3101, MATH UN2010, or equivalent), probability (IEOR E3658 or equivalent), and signals and systems (ELEN E3801), or instructor's permission. Introduces numerical tools for adaptive processing of signals. Signal representations, sparsity in overcomplete bases. Techniques for sparse recovery, applications to inpainting and denoising. Adaptive representations: principal component analysis, clustering and vector quantization, dictionary learning. Source separation: independent component analysis and matrix factorizations. Signal classification: support vector machines and boosting, learning with invariances. Hashing and signal retrieval. Case studies from image processing, audio, multimedia.

CSEE W4840y Embedded systems
3 pts. Lect: 3. Professor Edwards.
Prerequisite(s): CSEE W4823 or equivalent. Embedded system design and implementation combining hardware and software. I/O, interfacing, and peripherals. Weekly laboratory sessions and term project on design of a microprocessor-based embedded system including at least one custom peripheral. Knowledge of C programming and digital logic required.

CSEE E4868x or y System-on-chip platforms
3 pts. Lect: 3. Professor Carloni.
Prerequisite(s): COMS W3157 and CSEE W3827 Design and programming of System-on-Chip (SoC) platforms. Topics include overview of technology and economic trends, methodologies and supporting CAD tools for system-level design; models of computation, the SystemC language, transaction-level modeling, hardware-software partitioning, high-level synthesis, system programming, on-chip communication, memory organization, power management and optimization, integration of programmable processor cores and specialized accelerators. Case studies of modern SoC platforms for various classes of applications.

ELEN E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

ELEN E4900-4909x or y Topics in electrical and computer engineering
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): Instructor's permission. Selected topics in electrical and computer engineering. Content varies from year to year, and different topics rotate through the course numbers 4900 to 4909.

ELEN E4944x or y Principles of device microfabrication
3 pts. Lect: 3. Professor Trevino.
Science and technology of conventional and advanced microfabrication techniques for electronics, integrated and discrete components. Topics include diffusion; ion implantation, thin-film growth including oxides and metals, molecular beam and liquid-phase epitaxy; optical and advanced lithography; and plasma and wet etching.

ELEN E4998x or y Intermediate projects in electrical engineering
0–3 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Substantial independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

ELEN E6001x-E6002y Advanced projects in electrical engineering
1–4 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. May be repeated for up to 6 points of credit. Graduate-level projects in various areas of electrical engineering and computer science. In consultation with an instructor, each student designs their project depending on the student's previous training and experience. Students should consult with a professor in their area for detailed arrangements no later than the last day of registration.

ELEN E6003x and y Master's thesis
3 pts. Members of the faculty.
Prerequisite(s): A minimum of 3 points of credit in ELEN E6001 or E6002 advanced projects with the same instructor, instructor's permission, and completion of at least 12 points of credit in MS program with GPA of at least 3.5. Research in area of Electrical Engineering culminating in a verbal presentation and a written thesis document approved by thesis instructor. Must obtain permission from thesis instructor to enroll. Thesis projects span at least two terms: ELEN E6001 or E6002 Advanced Project followed by E6003 Master's Thesis with same instructor. Students must use department recommended format for thesis writing. Counts toward total amount of research credit in M.S. program.

ELEN E6010y Systems biology: design principles for biological circuits
4.5 pts. Lect: 3. Professor Jelenkovic.
Prerequisite(s): ECBM E4060 or instructor's permission. Beyond bioinformatics, cells as systems. Metabolic networks, transcription regulatory networks, signaling networks. Deterministic and stochastic kinetics. Mathematical representation of reconstructed networks. Network motifs. Signal transduction and neuronal networks. Robustness. Bacterial chemotaxis and patterning in fruit fly development. Kinetic proofreading. Optimal gene circuit design. Rules for gene regulation. Random networks and multiple time scales. Biological information processing. Numerical and simulation techniques. Major project(s) in MATLAB.

EEBM E6020y Methods of computational neuroscience
4.5 pts. Lect: 3.
Prerequisite(s): BMEB W4020 or instructor's permission. Formal methods in computational neuroscience including methods of signal processing, communications theory, information theory, systems and control, system identification and machine learning. Molecular models of transduction pathways. Robust adaptation and integral feedback. Stimulus representation and groups. Stochastic and dynamical systems models of spike generation. Neural diversity and ensemble encoding. Time encoding machines and neural codes. Stimulus recovery with time decoding machines. MIMO models of neural computation. Synaptic plasticity and learning algorithms. Major project(s) in MATLAB.

BMEE E6030x Neural modeling and neuroengineering
3 pts. Lect: 3. Professor Sajda.
Prerequisite(s): ELEN E3801 and either APMA E2101 or E3101, or equivalent, or instructor's permission. Engineering perspective on the study of multiple levels of brain organization, from single neurons to cortical modules and systems. Mathematical models of spiking neurons, neural dynamics, neural coding, and biologically based computational learning. Architectures and learning principles underlying both artificial and biological neural networks. Computational models of cortical processing, with an emphasis on the visual system. Applications of principles in neuroengineering; neural prostheses, neuromorphic systems and biomimetics. Course will include a computer simulation laboratory.

ECBM E6040y Neural networks and deep learning research.
3 pts. Lect: 3. Professor Lazar.
Prerequisite(s): ECBM E4040 or the equivalent. Regularized autoencoders, sparse coding and predictive sparse decomposition, denoising autoencoders, representation learning, manifold perspective on representation learning, structured probabilistic models for deep learning, Monte Carlo methods, training and evaluating models with intractable partition functions, restricted Boltzmann machines, approximate inference, deep belief networks, deep learning in speech, and object recognition.

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

CSEE E6180x or y Modeling and performance evaluation
3 pts. Lect: 2. Professor Misra.
Prerequisite(s): COMS W4118 and STAT GU4001 or instructor's permission. Introduction to queuing analysis and simulation techniques. Evaluation of time-sharing and multiprocessor systems. Topics include priority queuing, buffer storage, and disk access, interference and bus contention problems, and modeling of program behaviors.

ELEN E6201x Linear system theory
3 pts. Lect: 3. Professor Sun.
Prerequisite(s): ELEN E3801 and APMA E3101, or equivalents. Abstract objects, the concepts of state. Definition and properties of linear systems. Characterization of linear continuous-time and discrete-time, fixed, and time-varying systems. State-space description; fundamental matrix, calculation by computer and matrix methods. Modes in linear systems. Adjoint systems. Controllability and observability. Canonical forms and decompositions. State estimators. Lyapunov's method and stability.

ELEN E6302x or y MOS transistors
3 pts. Lect: 2. Professor Tsividis.
Prerequisite(s): ELEN E3106 or equivalent. Operation and modeling of MOS transistors. MOS two- and three-terminal structures. The MOS transistor as a four-terminal device; general charge-sheet modeling; strong, moderate, and weak inversion models; short-and-narrow-channel effects; ion-implanted devices; scaling considerations in VLSI; charge modeling; large-signal transient and small-signal modeling for quasistatic and nonquasistatic operation.

ELEN E6312y Advanced analog integrated circuits
3 pts. Lect: 2. Professor Krishnaswamy.
Prerequisite(s): ELEN E4312. Integrated circuit device characteristics and models; temperature- and supply-independent biasing; IC operational amplifier analysis and design and their applications; feedback amplifiers, stability and frequency compensation techniques; noise in circuits and low-noise design; mismatch in circuits and low-offset design. Computer-aided analysis techniques are used in homework or a design project.

ELEN E6314x Advanced communication circuits
3 pts. Lect: 2.
Prerequisite(s): ELEN E4314 and E6312. Overview of communication systems, modulation and detection schemes. Receiver and transmitter architectures. Noise, sensitivity, and dynamic range. Nonlinearity and distortion. Low-noise RF amplifiers, mixers, and oscillators. Phase-locked loops and frequency synthesizers. Typical applications discussed include wireless RF transceivers or data links. Computer-aided analysis techniques are used in homework(s) or a design project.

ELEN E6316y Analog-digital interfaces in VLSI
3 pts. Lect: 3. Professor Dickson.
Prerequisite(s): ELEN E4312 or equivalent. Analog-to-digital and digital-to-analog conversion techniques for very large scale integrated circuits and systems. Precision sampling; quantization; A/D and D/A converter architectures and metrics; Nyquist architectures; oversampling architectures;

correction techniques; system considerations. A design project is an integral part of this course.

ELEN E6318x or y Microwave circuit design
3 pts. Lect: 3. Professor Baeyens.
Prerequisite(s): ELEN E3331 and E3401, or equivalents. Introduction to microwave engineering and microwave circuit design. Review of transmission lines. Smith chart, S-parameters, microwave impedance matching, transformation and power combining networks, active and passive microwave devices, S-parameter-based design of RF and microwave amplifiers. A microwave circuit design project (using microwave CAD) is an integral part of the course.

ELEN E6320x or y Millimeter-wave IC design
3 pts. Lect: 3. Professor Krishnaswamy.
Prerequisite(s): ELEN E3401 or equivalent, ELEN E4314 and E6312. Principles behind the implementation of millimeter-wave (30GHz-300GHz) wireless circuits and systems in silicon-based technologies. Silicon-based active and passive devices for millimeter-wave operation, millimeter-wave low-noise amplifiers, power amplifiers, oscillators and VCOs, oscillator phase noise theory, mixers and frequency dividers for PLLs. A design project is an integral part of the course.

EECS E6321y Advanced digital electronic circuits
3 pts. Lect: 2. Professor Seok.
Prerequisite(s): EECS E4321. Advanced topics in the design of digital integrated circuits. Clocked and non-clocked combinational logic styles. Timing circuits: latches and flip-flops, phase-locked loops, delay-locked loops. SRAM and DRAM memory circuits. Modeling and analysis of on-chip interconnect. Power distribution and power-supply noise. Clocking, timing, and synchronization issues. Circuits for chip-to-chip electrical communication. Advanced technology issues that affect circuit design. The class may include a team circuit design project.

EECS E6322x VLSI Hardware architecture for signal processing and machine learning
3 pts. Lect: 3. Professor Seok.
Prerequisite(s): CSEE W3827 and ELEN E3801. Recommended: ELEN E4810. Design of digital VLSI hardware for various digital signal processing and machine learning algorithms. Data flow graphs, iteration bounds, pipelining, parallel architectures, retiming, unfolding/folding, systolic architectures, bit-level arithmetic, numerical and algorithmic strength reductions, CORDIC, distributed arithmetic, FFT, neural network hardware, vector processors, subwordparallel architecture, and SIMD. May include a team circuit design project.

ELEN E6324x or y Principles of RF and microwave measurement
3 pts. Lect: 3. Professor Shahramian.
Prerequisite(s): ELEN E4314 or equivalent, or instructor's permission. Principles behind, and techniques related to, RF and microwave simulation and measurements. S parameters; simulations and measurements for small-signal and large signal / nonlinear circuits in the time and frequency domains; noise.

ELEN E6331y Principles of semiconductor physics, I
3 pts. Lect: 2. Professor Wang.
Prerequisite(s): ELEN E4301. Designed for students interested in research in semiconductor materials and devices. Topics include energy bands: nearly free electron and tight-binding approximations, the k.p. method, quantitative calculation of band structures and their applications to quantum structure transistors, photodetectors, and lasers; semiconductor statistics, Boltzmann transport equation, scattering processes, quantum effect in transport phenomena, properties of heterostructures. Quantum mechanical treatment throughout.

ELEN E6332y Principles of semiconductor physics, II
3 pts. Lect: 2.
Prerequisite(s): ELEN E3106 or ELEN E6331. Optical properties including absorption and emission of radiation, electron-phonon interactions, radiative and phonon-mediated processes, excitons, plasmons, polaritons, carrier recombination and generation, and related optical devices, tunneling phenomena, superconductivity. Quantum mechanical treatment throughout, heavy use of perturbation theory.

ELEN E6333y Semiconductor device physics
3 pts. Lect: 2.
Prerequisite(s): ELEN E3106 or ELEN E4301 or equivalent. Physics and properties of semiconductors. Transport and recombination of excess carriers. Schottky, P-N, MOS, and heterojunction diodes. Field effect and bipolar junction transistors. Dielectric and optical properties. Optical devices including semiconductor lamps, lasers, and detectors.

ELEN E6340x Power management integrated circuits
3 pts. Lect: 3.
Prerequisite(s): ELEN E4312 or ELEN E4361. Modern power management integrated circuits (PMIC) design introduced comprehensively. Advanced topics in power management introduced, including linear regulators, digital linear regulators, switch-mode power converters, control schemes for DC-DC converters, compensation methods of DC-DC converters, power losses in DC-DC converters, switched capacitor converters, power converter modeling and simulation, design examples.

ELEN E6350y VLSI design laboratory
3 pts. Lab: 3. Professor Kinget.
Prerequisite(s): ELEN E4321 and E4312, or instructor's permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E4350, but the complexity requirements of integrated circuits are higher.

ELEN E6412y Lightwave devices
3 pts. Lect: 2. Professor Woodward.
Prerequisite(s): ELEN E4411. Electro-optics: principles; electro-optics of liquid crystals and photo-refractive materials. Nonlinear optics: second-order nonlinear optics; third-order nonlinear optics; pulse propagation and solitons. Acousto-optics: interaction of light and sound; acousto-optic devices. Photonic switching and computing: photonic switches; all-optical switches; bistable optical devices. Introduction to fiber-optic communications: components of the fiber-optic link; modulation, multiplexing and coupling; system performance; receiver sensitivity; coherent optical communications.

ELEN E6413y Lightwave systems
3 pts. Lect: 2. Professor Feuer.
Prerequisite(s): ELEN E4411. Recommended preparation: ELEN E6412. Fiber optics. Guiding, dispersion, attenuation, and nonlinear properties of fibers. Optical modulation schemes. Photonic components, optical amplifiers. Semiconductor laser transmitters. Receiver design. Fiber optic telecommunication links. Nonregenerative transmission using erbium-doped fiber amplifier chains. Coherent detection. Local area networks. Advanced topics in light wave networks.

ELEN E6414y Photonic integrated circuits
3 pts. Lect: 3.
Photonic integrated circuits are important subsystem components for telecommunications, optically controlled radar, optical signal processing, and photonic local area networks. An introduction to the devices and the design of these circuits. Principle and modeling of dielectric waveguides (including silica on silicon and InP based materials), waveguide devices (simple and star couplers), and surface diffractive elements. Discussion of numerical techniques for modeling circuits, including beam propagation and finite difference codes, and design of other devices: optical isolators, demultiplexers.

ELEN E6430x or y Applied quantum optics
3 pts. Lect: 2.
Prerequisite(s): Background in electromagnetism (ELEN E3401, E4401, E4411, or PHYS GR6092) and quantum mechanics (APPH E3100, E4100, or PHYS GU402x). An introduction to fundamental concepts of quantum optics and quantum electrodynamics with an emphasis on applications in nanophotonic devices. The quantization of the electromagnetic field; coherent and squeezed states of light; interaction between light and electrons in the language of quantum electrodynamics (QED); optical resonators and cavity QED; low-threshold lasers; and entangled states of light.

ELEN E6488y Optical interconnects and interconnection networks
3 pts. Lect: 2. Professor Bergman.
Prerequisite(s): ELEN E4411 or E4488 or an equivalent photonics course. Introduction to optical interconnects and interconnection networks for digital systems. Fundamental optical interconnects technologies, optical interconnection network design, characterization, and performance evaluation. Enabling photonic technologies including free-space structures, hybrid and monolithic integration platforms for photonic on-chip, chip-to-chip, backplane, and

node-to-node interconnects, as well as photonic networks on-chip.

EEME E6601x Introduction to control theory
3 pts. Lect: 3. Professor Longman.
Prerequisite(s): MATH UN2030. A graduate-level introduction to classical and modern feedback control that does not presume an undergraduate background in control. Scalar and matrix differential equation models, and solutions in terms of state transition matrices. Transfer functions and transfer function matrices, block diagram manipulations, closed-loop response. Proportional, rate, and integral controllers, and compensators. Design by root locus and frequency response. Controllability, observability. Luenberger observers, pole placement, and linear-quadratic cost controllers.

EEOR E6616x or y Convex optimization
3 pts. Lect: 3. Professor Iyengar.
Prerequisite(s): IEOR E6613 and EEOR E4650. Convex sets and functions, and operations preserving convexity. Convex optimization problems. Convex duality. Applications of convex optimization problems ranging from signal processing and information theory to revenue management. Convex optimization in Banach spaces. Algorithms for solving constrained convex optimization problems.

EECS E6690-6699x or y Topics in data-driven analysis and computation
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): the instructor's permission. Selected advanced topics in data-driven analysis and computation. Content varies from year to year, and different topics rotate through the course numbers 6690 to 6699.

ELEN E6711x Stochastic models in information systems
4.5 pts. Lect: 3. Professor Baryshnikov.
Prerequisite(s): IEOR E3658. Foundations: probability review, Poisson processes, discrete-time Markov models, continuous-time Markov models, stationarity, and ergodicity. The course presents a sample-path (time domain) treatment of stochastic models arising in information systems, including at least one of the following areas: communications networks (queueing systems), biological networks (hidden Markov models), Bayesian restoration of images (Gibbs fields), and electric networks (random walks).

ELEN E6712x Communication theory
3 pts. Lect: 3.
Prerequisite(s): ELEN E4815, or equivalent, or instructor's permission. Representation of bandlimited signals and systems. Coherent and incoherent communications over Gaussian channels. Basic digital modulation schemes. Intersymbol inference channels. Fading multipath channels. Carrier and clock synchronization.

ELEN E6713y Topics in communications
3 pts. Lect: 3.
Prerequisite(s): ELEN E6712 or E4702 or E4703 or equivalent, or instructor's permission. Advanced topics in communications, such as turbo codes, LDPC codes, multiuser communications, network coding, cross-layer optimization, cognitive radio. Content may vary from year to year to reflect the latest development in the field.

ELEN E6717x Classical and Quantum Information Theory
3 pts. Lect: 2. Professor X. Wang.
Prerequisite(s): IEOR E3658 or a course in stochastic processes. Classical and quantum information measures. Source coding theorem. Capacity of discrete memoryless channels and the noisy channel coding theorem. The rate-distortion theory. Gaussian channel capacity. Quantum source coding. Quantum channel capacity.

ELEN E6718y Error correcting codes: classical and modern
3 pts. Lect: 2. Professor Ashikhmin.
Prerequisite(s): IEOR E3658. Main concepts of error control codes. Linear block codes. Elements of algebra: Galois fields. BCH and Reed Solomon codes. Convolutional Codes. Modern, capacity-achieving codes: Low Density Parity Check codes, TURBO codes, and Polar codes. EXIT Charts analysis.

EECS E6720 Bayesian models for machine learning
3 pts. Lect: 3. Professor Paisley.
Prerequisite(s): Basic calculus, linear algebra, probability, and programming. Basic statistics and machine learning strongly recommended. Bayesian approaches to machine learning. Topics include mixed-membership models, latent factor models, Bayesian nonparametric methods, probit classification, hidden Markov models, Gaussian mixture models, model learning with mean-field variational inference, scalable inference for Big Data. Applications include image processing, topic modeling, collaborative filtering, and recommendation systems.

ELEN E6730y Quantum Sensing Theory
3 pts. Lect: 3. Professor X. Wang.
Prerequisite(s): Linear Algebra. Introduction to quantum detection and estimation theory and its applications to quantum communications, quantum radar, quantum metrology, and quantum tomography. Background on quantum mechanics, quantum detection, composite quantum systems, Gaussian states, and quantum estimation.

ELEN E6761x Computer communication networks I
3 pts. Lect: 3. Professor Ghaderi.
Prerequisite(s): IEOR E3658 or equivalent, or instructor's permission. Recommended: CSEE W4119. Analytical approach to the design of (data) communication networks. Necessary tools for performance analysis and design of network protocols and algorithms. Practical engineering applications in layered internet protocols in Data link layer, Network layer, and Transport layer. Review of relevant aspects of stochastic processes, control, and optimization.

EECS E6765 Internet of things—systems and physical data analytics
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): Knowledge of programming; ELEN E4703 or related; or CSEE W4119; or instructor's permission. Internet of Things from the point of view of data. Methods for data analytics to understand trade-offs and partitioning between cloud-based data-analytics and physical-device data analytics. Two-way interaction between data and physical devices to support a truly ubiquitous, networked, and autonomous cyber-physical ecosystem. System-focused design of architectures, algorithms, networks, protocols, communications, power, security, and standards. Focus on a significant design project.

ELEN E6767x or y Internet economics, engineering, and the implications for society
3 pts. Lect: 2. Professor Mitra.
Prerequisite(s): CSEE W4119 or ELEN E6761 recommended, and ability to comprehend and track development of sophisticated models. Mathematical models, analyses of economics and networking interdependencies in the internet. Topics include microeconomics of pricing and regulations in communications industry, game theory in revenue allocations, ISP settlements, network externalities, two-sided markets. Economic principles in networking and network design, decentralized vs. centralized resource allocation, "price of anarchy," congestion control. Case studies of topical internet issues. Societal and industry implications of internet evolution.

ELEN E6770–6779x or y Topics in networking
3 pts. Lect: 2. Members of the faculty.
Further study of areas such as communication protocols and architectures, flow and congestion control in data networks, performance evaluation in integrated networks. Content varies from year to year, and different topics rotate through the course numbers 6770 to 6779.

ELEN E6820y Speech and audio processing and recognition
3 pts. Lect: 2. Professor Mesgarani.
Prerequisite(s): ELEN E4810 or instructor's permission. Fundamentals of digital speech processing and audio signals. Acoustic and perceptual basics of audio. Short-time Fourier analysis. Analysis and filter bank models. Speech and audio coding, compression, and reconstruction. Acoustic feature extraction and classification. Recognition techniques for speech and other sounds, including hidden Markov models.

CSEE E6824y Parallel computer architecture
3 pts. Lect: 2.
Prerequisite(s): CSEE W4824. Parallel computer principles, machine organization and design of parallel systems including parallelism detection methods, synchronization, data coherence and interconnection networks. Performance analysis and special purpose parallel machines.

CSEE E6847y Distributed embedded systems
3 pts. Lect: 2.
Prerequisite(s): Any COMS W411X, CSEE W48XX, or ELEN E43XX course, or instructor's permission. An interdisciplinary graduate-level seminar on the design of distributed embedded systems. System

robustness in the presence of highly variable communication delays and heterogeneous component behaviors. The study of the enabling technologies (VLSI circuits, communication protocols, embedded processors, RTOSs), models of computation, and design methods. The analysis of modern domain-specific applications including on-chip micro-networks, multiprocessor systems, fault-tolerant architectures, and robust deployment of embedded software. Research challenges such as design complexity, reliability, scalability, safety, and security. The course requires substantial reading, class participation and a research project.

ELEN E6860y Advanced digital signal processing
3 pts. Lect: 2. Professor Nguyen.
Prerequisite(s): ELEN E4810. This course is designed as an extension to ELEN E4810, with emphasis on emerging techniques in the area of digital signal processing. Topics include multirate signal processing, multidimensional signal processing, short-time Fourier transform, signal expansion in discrete and continuous time, filter banks, multiresolution analysis, wavelets, and their applications to image compression and understanding. Other topics may be included to reflect developments in the field.

CSEE E6861y Computer-aided design of digital systems
3 pts. Lect: 2. Professor Nowick.
Prerequisite(s): (i) one semester of advanced digital logic (CSEE W4823 or equivalent, or instructor's permission); and (ii) a basic course in data structures and algorithms (COMS W3133, W3134, W3137, W3139 or W3157, or equivalent), and familiarity with programming. Introduction to modern digital CAD synthesis and optimization techniques. Topics include modern digital system design (high-level synthesis, register-transfer level modeling, algorithmic state machines, optimal scheduling algorithms, resource allocation and binding, retiming), controller synthesis and optimization, exact and heuristic two-level logic minimization, advanced multi-level logic optimization, optimal technology mapping to library cells (for delay, power and area minimization), advanced data structures (binary decision diagrams), SAT solvers and their applications, static timing analysis, and introduction to testability. Includes hands-on small design projects using and creating CAD tools.

CSEE E6863 Formal verification of hardware and software systems
3 pts. Lect: 2. Professor Theobald and Ivancic.
Prerequisite(s): COMS W3134, W3136, or W3137 and COMS W3261. Introduction to the theory and practice of formal methods for the design and analysis of correct (i.e., bug-free) concurrent and embedded hardware/software systems. Topics include temporal logics; model checking; deadlock and liveness issues; fairness; satisfiability (SAT) checkers; binary decision diagrams (BDDs); abstraction techniques; introduction to commercial formal verification tools. Industrial state-of-the-art, case studies and experiences: software analysis (C/C++/Java), hardware verification (RTL).

CSEE E6868x or y Embedded scalable platforms
3 pts. Lect: 2. Professor Carloni.
Prerequisite(s): CSEE W4868 or instructor's permission. Inter-disciplinary graduate-level seminar on design and programming of embedded scalable platforms. Content varies between offerings to cover timely relevant issues and latest advances in system-on-chip design, embedded software programming and electronic design automation. Requires substantial reading of research papers, class participation, and semester-long project.

EECS E6870x or y Speech recognition
3 pts. Lect: 2.
Prerequisite(s): Basic probability and statistics. Theory and practice of contemporary automatic speech recognition. Gaussian mixture distributions, hidden Markov models, pronunciation modeling, decision trees, finite-state transducers, and language modeling. Selected advanced topics will be covered in more depth.

ELEN E6873x or y Statistical signal processing and learning
3 pts. Lect: 2. Professor Jajamovich.
Prerequisite(s): ELEN E4815. Introduction to the fundamental principles of statistical signal processing related to detection and estimation. Hypothesis testing, signal detection, parameter estimation, signal estimation, and selected advanced topics. Suitable for students doing research in communications, control, signal processing, and related areas.

ELEN E6876x or y Sparse and low-dimensional models for high-dimensional data
3 pts. Lect: 3. Professor Wright.
Prerequisite(s): ELEN E4815 or equivalent and linear algebra. Recommended: ELEN E4810 or equivalent. Overview of theory, computation and applications for sparse and low-dimensional data modeling. Recoverability of sparse and low-rank models. Optimization methods for low-dim data modeling. Applications to imaging, neuroscience, communications, web data.

ELEN E6880-6889x or y Topics in signal processing
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): ELEN E4810. Advanced topics in signal processing, such as multidimensional signal processing, image feature extraction, image/video editing and indexing, advanced digital filter design, multirate signal processing, adaptive signal processing, and wave-form coding of signals. Content varies from year to year, and different topics rotate through the course numbers 6880 to 6889.

EECS E6890-6899x or y Topics in information processing
3 pts. Lect: 2. Members of the faculty.
Advanced topics spanning electrical engineering and computer science such as speech processing and recognition, image and multimedia content analysis, and other areas drawing on signal processing, information theory, machine learning, pattern recognition, and related topics. Content varies from year to year, and different topics rotate through the course numbers 6890 to 6899.

ELEN E6900–6909x or y Topics in electrical and computer engineering
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): Instructor's permission. Selected topics in electrical and computer engineering. Content varies from year to year, and different topics rotate through the course numbers 6900 to 6909.

ELEN E6910-6919x or y Topics in technical writing and presentation for electrical engineers
1 pt. Professor Kayfetz.
Open to M.S. and Ph.D. students in EE/CE with instructor's permission. Topics to help EE/CE graduate students' communication skills. Emphasis on writing clear, concise proposals, journal articles, conference papers, and theses, and on preparing clear technical presentations. Different topics rotate through the course numbers 6910 to 6919. May be repeated for credit. Credit may not be used to satisfy degree requirements.

CSEE E6915y Technical writing for computer scientists and engineers
3 pts. Members of the faculty.
Available to M.S. or Ph.D. candidates in CS/CE. Topics to help CS/CE and EE graduate students' communication skills. Emphasis on writing, presenting clear, concise proposals, journal articles, conference papers, theses, and technical presentations. Credit may not be used to satisfy degree requirements.

ELEN E6945x or y Device nanofabrication
3 pts. Lect: 3.
Prerequisite(s): ELEN E3106 and E3401, or equivalents. Recommended: ELEN E4944. This course provides an understanding of the methods used for structuring matter on the nanometer length: thin-film technology; lithographic patterning and technologies including photon, electron, ion and atom, scanning probe, soft lithography, and nanoimprinting; pattern transfer; self-assembly; process integration; and applications.

ELEN E6950x Wireless and mobile networking, I
4.5 pts. Lect: 2. Lab: 1. Professor Jelenkovic.
Corequisite(s): ELEN E6761 or instructor's permission. Overview of mobile and wireless networking. Fundamental concepts in mobile wireless systems: propagation and fading, cellular systems, channel assignment, power control, handoff. Examples of second-generation circuits-switched systems and standards. Quantitative homework assignments may require use of a mathematical software package.

ELEN E6999x, y, or s Fieldwork
0.5–1.5 pts. Members of the faculty.
Prerequisite(s): Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used for

degree credit. Only for electrical engineering and computer engineering graduate students who include relevant off-campus work experience as part of their approved program of study. Final report required. May not be taken for pass/fail credit or audited.

EEME E8601y Advanced topics in control theory
3 pts. Lect: 3. Members of the faculty.
See entry under “Courses in Mechanical Engineering” for description.

ELEN E9001x and y–E9002 Research
0–6 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. Points of credit to be approved by the department. Requires submission of an outline of the proposed research for approval by the faculty member who is to supervise the work of the student. The research facilities of the department are available to qualified students interested in advanced study.

ELEN E9011x and y–E9012 Doctoral research
0–6 pts. Members of the faculty.
Prerequisite(s): Requires approval by a faculty member who agrees to supervise the work. Points of credit to be approved by the department. Open only to doctoral students who have passed the qualifying examinations. Requires submission of an outline of the proposed research for the approval of the faculty member who is to supervise the work of the student.

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

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

COURSES IN ELECTRICAL ENGINEERING OFFERED OCCASIONALLY

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

EEHS E3900y History of telecommunications: from the telegraph to the internet
3 pts. Lect: 3.
Historical development of telecommunications from the telegraphy of the mid-1800s 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. The social needs that elicited new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are explained as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking principles. There are no prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective. The course shares lectures with EEHS E4900, but the work requirements differ somewhat.

ELEN E3999x or y Electrical engineering design challenge
1 pt.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Short-term design project organized as a faculty-led team competition. Particular design targets are set that vary by semester. A set of hardware and software constraints is specified. The project takes place over an advertised subset of the semester, beginning around the third week.

BMEE E4030y Neural control engineering
3 pts. Lect: 3.
Prerequisite(s): ELEN E3801. Topics include basic cell biophysics, active conductance and the Hodgkin-Huxley model, simple neuron models, ion channel models and synaptic models, statistical models of spike generation, Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, sensorimotor integration and optimal state estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and somatosensory pathway, neural encoding model: spike triggered average (STA) and spike triggered covariance (STC) analysis, neuronal response to electrical micro-stimulation, DBS for Parkinson’s disease treatment, motor neural prostheses, and sensory neural prostheses.

ELEN E4215y Analog filter synthesis and design
3 pts. Lect: 3.
Prerequisite(s): ELEN E3201 and ELEN E3801, or equivalent. Approximation techniques for magnitude, phase, and delay specifications, transfer function realization sensitivity, passive LC filters, active RC filters, MOSFET-C filters, Gm-C filters, switched-capacitor filters, automatic tuning techniques for integrated filters. Filter noise. A design project is an integral part of the course.

ELEN E4301y Introduction to semiconductor devices
3 pts. Lect: 3.
Prerequisite(s): ELEN E3106 or equivalent. Semiconductor physics. Carrier injection and recombination. P-n junction and diodes: Schottky barrier and heterojunctions, solar cells and light-emitting diodes. Junction and MOS field-effect transistors, bipolar transistors. Tunneling and charge-transfer devices.

ELEN E4302x or y Magnetic sensors and instruments for medical imaging
3 pts. Lect: 2.5, Lab: 0.5.
Prerequisite(s): ELEN E3106, ELEN E3401, or instructor’s permission. Physics of nuclear magnetic resonance (NMR) and superconducting quantum interference device (SQUID). Design and operation of superconducting DC magnet, RF receiver, Josephson junction, and integrated SQUID. Principles of biomedical sensoring systems including Magnetic Resonance Imaging (MRI), SQUID magnetometer, and NMR spectroscopy. Medical image formation and processing.

ELEN E4350y VLSI design laboratory
3 pts. Lab: 3.
Prerequisite(s): EECS E4321 and ELEN E4312, or instructor’s permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E6350, but the complexity requirements of integrated circuits are lower.

BMEE E4400x Wavelet applications in biomedical image and signal processing
3 pts. Lect: 3.
Prerequisite(s): APMA E2101 or E3101 or equivalent. An introduction to methods of wavelet analysis and processing techniques for the quantification of biomedical images and signals. Topics include frames and overcomplete representations, multiresolution algorithms for denoising and image restoration, multiscale texture segmentation, and classification methods for computer-aided diagnosis.

ELEN E4401x Wave transmission and fiber optics
3 pts. Lect: 3.
Prerequisite(s): ELEN E3401 or equivalent. Waves and Maxwell’s equations. Field energetics, dispersion, complex power. Waves in dielectrics and in conductors. Reflection and refraction. Oblique incidence and total internal reflection. Transmission lines and conducting waveguides. Planar and circular dielectric waveguides; integrated optics and optical fibers. Hybrid and LP modes. Graded-index fibers. Mode coupling; wave launching.

ELEN E4420x Topics in electromagnetics
3 pts. Lect: 3.
Prerequisite(s): Undergraduate electromagnetic theory. Selected topics in the theory and practice of electromagnetics, varying from year to year. Topic for current term will be available in the department office one month before registration. This course may be taken more than once when topics are different. Possible topics: microwave theory and design (generalized waveguides, excitation and coupling of waveguides, junctions, microwave networks, periodic structures, optical fibers); antennas (filamentary antennas, arrays, aperture radiation, system properties, pattern synthesis); electrodynamics (special relativity, radiation by charged particles, relativistic beams, free electron lasers).

ELEN E4501x Electromagnetic devices and energy conversion
3 pts. Lect: 3. Professor Sen.
Prerequisite(s): ELEN E3401. Linear and nonlinear magnetic circuits. Electric and magnetic energy storage, loss, and transfer. Circuit behavior of energy storage and transfer devices. Field theory of moving bodies. Dynamical equations of an electromechanical system. Electromechanical and thermo-electric sensors and actuators. Rotating electric energy converters. Superconductivity and applications.

ELEN E4503x Sensors, actuators, and electromechanical systems
3 pts. Lect: 3.
Prerequisite(s): ELEN E3201 and E3401, or equivalents. Electromagnetic energy storage, loss, and transfer. Dynamics of electromechanical systems. Linearization of nonlinear coupled dynamical equations and equivalent circuits. Electromechanical actuators: acoustic, IC-processed micromachines. Electromechanical sensors: acoustic, pressure, and acceleration. Thermal sensors: polysilicon thermopiles and bipolar transistor temperature sensors. Electro-optic sensors: visible light, infrared, and X-ray.

ELEN E4510x or y Solar energy and smart grid power systems
3 pts. Lect: 3. Professors Kymissis and Schwartz.
Prerequisite(s): Background in circuits. Inorganic solar cell semiconductor physics. Single and tandem junction design. Measures of spectral and energy efficiency. Introduction to organic solar cells and thin film inorganic cells. Batteries and other energy storage systems. Introduction to legacy power networks: Single phase equivalents to three-phase networks. Reactive and real power. Equivalent circuits of synchronous machines, transformers, and transmission lines. Smart grid technology: Control and management of distributed solar energy and other intermittent renewable power sources connected to legacy power networks. Microgrid concept. “Small world” networks and fault management. Communication over power lines. Smart metering.

ELEN E4896y Music signal processing
3 pts. Lect: 3.
Prerequisite(s): ELEN E3801, E4810, or the equivalent. An investigation of the applications of signal processing to music audio, spanning the synthesis of musical sounds (including frequency modulation [FM], additive sinusoidal synthesis, and linear predictive coding [LPC]), the modification of real and synthetic sounds (including reverberation and time/pitch scaling), and the analysis of music audio to extract musical information (including pitch tracking, chord transcription, and music matching). Emphasis on practical, hands-on experimentation, with a wide range of software implementations introduced and modified within the class.

ECBM E6070–6079x or y Topics in neuroscience and deep learning
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): the instructor's permission. Selected advanced topics in neuroscience and deep learning. Content varies from year to year, and different topics rotate through the course numbers 6070 to 6079.

ELEN E6080–6089x or y Topics in systems biology
3 pts. Lect: 2. Members of the faculty.
Prerequisite(s): Instructor’s permission. Selected advanced topics in systems biology. Content varies from year to year, and different topics rotate through the course numbers 6080 to 6089.

ELEN E6151y Surface physics and analysis of electronic materials
3 pts. Lect: 2.
Prerequisite(s): Instructor’s permission. Basic physical principles of methods of surface analysis, surfaces of electronic materials including structure and optical properties (auger electron spectroscopy, X-ray photoemission, ultraviolet photoelectron spectroscopy, electron energy loss spectroscopy, inverse photoemission, photo stimulated desorption, and low energy electron diffraction), physical principles of each approach.

ELEN E6211x or y Circuit theory
3 pts. Lect: 3.
Prerequisite(s): ELEN E3331 and ELEN E3801. An axiomatic development of circuit theory. Circuit theorems, circuit topology, general methods of circuit analysis. Normal form characterizations. Scattering characterization and sensitivity function. Basic network synthesis methods: immittance and transfer function realization, multiport realization, approximation techniques.

ELEN E6261y Computational methods of circuit analysis
3 pts. Lect: 3.
Prerequisite(s): ELEN E3331 and APMA E3101. Computational algorithms for DC, transient, and frequency analysis of linear and nonlinear circuits. Formulation of equations: state equations, hybrid equations, sparse tableaux. Solution techniques: iterative methods to solve nonlinear algebraic equations; piecewise linear methods; sparse matrix techniques; numerical integration of stiff, nonlinear differential equations, companion network models; waveform relaxation.

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

EEME E6602y Modern control theory
3 pts. Lect: 3.
Prerequisite(s): EEME E6601 or E4601 or ELEN E6201, or instructor’s permission. Singular value decomposition. ARX model and state-space model system identification. Recursive least squares filters and Kalman filters. LQR, H, linear robust control, predictive control. Learning control, repetitive control, adaptive control. Liapunov and Popov stability. Nonlinear adaptive control, nonlinear robust control, sliding mode control.

EEME E6610x Optimal control theory
3 pts. Lect: 3.
Prerequisite(s): ELEN E6201 or EEME E6601. Objectives of optimal control. Continuous and discrete control problems. Calculus of variations: Mayer and Bolza; Pontryagin’s maximum principle. Bang-bang and singular controls. Existence of optimal control. Hamilton-Jacobi theory and dynamic programming. Numerical methods. Optimal feedback control regulatory problems. Linear-quadratic-Gaussian estimation. Applications.

ELEN E6762y Computer communication networks, II
3 pts. Lect: 2.
Prerequisite(s): ELEN E6761. Broadband ISDN, services and protocols; ATM. Traffic characterization and modeling: Markov-modulated Poisson and Fluid Flow processes; application to voice, video, and images. Traffic Management in ATM networks: admission and access control, flow control. ATM switch architectures; input/output queueing. Quality of service (QoS) concepts.

EECS E6766x Internet of things—engineering innovations and commercialization
3 pts. Lect: 3. Professor Kostic.
Prerequisite(s): Basic programming and instructor’s permission. Deep dive into a couple of selected topics/use-cases from the area of Internet of Things. Coverage of the topic from device to the cloud, with focus on practical aspects. Innovative product definition, product development, marketing, commercialization, and monetization. Cross-disciplinary coverage: EE, MechE, CS, Bioengineering, marketing, business, design. Building products and start-ups in the IoT domain. Collaboration between the Engineering School, Business School, industry experts, and engagement in IoT activities in NYC. Collaborative project by groups of students from different disciplines. This course shares lectures with E4766, but a more complex project is expected.

ELEN E6781y Topics in modeling and analysis of random phenomena
3 pts. Lect: 3.
Prerequisite(s): 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 to reflect student interest and current developments in the field.

ELEN E6850x Visual information systems
3 pts. Lect: 2.
Prerequisite(s): ELEN E4830 or instructor's permission. Introduction to critical image technologies in advanced visual information systems, such as content-based image databases, video servers, and desktop video editors. Intended for graduate students. Topics include visual data representation and compression, content-based visual indexing and retrieval, storage system design (data placement, scheduling, and admission control), compressed video editing, and synchronization issues of stored video/audio signals. Programming projects and final presentations are required.

ELEN E6920x or y Topics in VLSI systems design
3 pts. Lect: 2.
Prerequisite(s): ELEN E4321. Design automation: layout, placement, and routing. Circuit simulation algorithms and optimization of performance and area. Multiprocessor computing systems. Verification of testing. Topics may change from year to year.

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.
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.
Prerequisite(s): 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.
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(s): ELEN E4411. Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent experimental and theoretical developments in various areas of photonics research. Examples of topics that may be treated include squeezed-light generation, quantum optics, photon detection, nonlinear optical effects, and ultrafast optics.

ELEN E9404x or y Seminar in lightwave communications
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's approval. Recent theoretical and experimental developments in light wave communications research. Examples of topics that may be treated include information capacity of light wave channels, photonic switching, novel light wave network architectures, and optical neural networks.

ELEN E9501x or y Seminar in electrical power networks
3 pts. Lect: 2.
Prerequisite(s): Open to doctoral candidates, and to qualified M.S. candidates with the instructor's permission. Recent developments in control & optimization for power systems, design of smart grid, and related topics.

EECS E9601x or y Seminar in data-driven analysis and computation
3 pts. Lect: 2.
Prerequisite(s): Open to doctoral candidates and qualified M.S. candidates with the instructor's permission. Advanced topics and recent developments in mathematical techniques and computational tools for data science and engineering problems.

ELEN E9701x or y Seminar in information and communication theories
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent developments in telecommunication networks, information and communication theories, and related topics.

ELEN E9705x or y Seminar in cyber-physical systems
3 pts.
Open to doctoral candidates and to qualified M.S. candidates with instructor's permission. Advanced topics in recent developments in research on cyber-physical systems (CPS) and related topics.

ELEN E9801x or y Seminar in signal processing
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's approval. Recent developments in theory and applications of signal processing, machine learning, content analysis, and related topics.

INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

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Industrial engineering is the branch of the engineering profession that is concerned with the design, analysis, and control of production and service systems. Originally, an industrial engineer worked in a manufacturing plant and was involved only with the operating efficiency of workers and machines. Today, industrial engineers are more broadly concerned with productivity and all of the technical problems of production management and control. They may be found in every kind of organization: manufacturing, distribution, transportation, mercantile, and service. Their responsibilities range from the design of unit operations to that of controlling complete production and service systems. Their jobs involve the integration of the physical, financial, economic, computer, and human components of such systems to attain specified goals. Industrial engineering includes activities such as production planning and control; quality control; inventory, equipment, warehouse, and materials management; plant layout; and workstation design.

Operations research is concerned with quantitative decision problems, generally involving the allocation and control of limited resources. Such problems arise, for example, in the operations of industrial firms, financial institutions, health care organizations, transportation systems, and government. The operations research analyst develops and uses mathematical and statistical models to help solve these decision problems. Like engineers, they are problem formulators and solvers. Their work requires the formation of a mathematical model of a system and the analysis and prediction of the consequences of alternate modes of operating the system. The analysis may involve mathematical optimization techniques, probabilistic and statistical methods, experiments, and computer simulations.

Management Science and Engineering (also known as Engineering Management Systems) is a multidisciplinary field integrating industrial engineering, operations research, contemporary technology, business, economics, and management. It provides a foundation for decision making and managing risks in complex systems.

Financial engineering is a multidisciplinary field integrating financial theory with economics, methods of engineering, tools of mathematics, and practice of programming. The field provides training in the application of engineering methodologies and quantitative methods to finance.

Business Analytics involves the use of data science tools for solving operational and marketing problems. Students learn to leverage advanced quantitative models, algorithms, and data for making actionable decisions to improve business operations.

Current Research Activities

In industrial engineering, research is conducted in the area of logistics, routing, scheduling, production and supply chain management, inventory control, revenue management, and quality control.

In operations research, new developments are being explored in mathematical programming, combinatorial optimization, stochastic modeling, computational and mathematical finance, queueing theory, reliability, simulation, and both deterministic and stochastic network flows.

In engineering and management systems, research is conducted in the areas of logistics, supply chain optimization, and revenue and risk management.

In financial engineering, research is being carried out in portfolio management; option pricing, including exotic and real options; computational finance, such as Monte Carlo simulation and numerical methods; as well as data mining and risk management.

Projects are sponsored and supported by leading private firms and government agencies. In addition, our students and faculty are involved in the work of four research and educational centers: the Center for Applied Probability (CAP), the Center for Financial Engineering (CFE), the Computational and Optimization Research Center (CORC), and the FDT Center for Intelligent Asset Management.

The Center for Applied Probability (CAP) is a cooperative center involving the School of Engineering and Applied Science, several departments in the Graduate School of Arts and Sciences, and Columbia Business School. Its interests are in four applied areas: mathematical and computational finance, stochastic networks, logistics and distribution, and population dynamics.

The Center for Financial Engineering (CFE) at Columbia University encourages interdisciplinary research in financial engineering and mathematical modeling in finance and promoting collaboration between Columbia faculty and financial institutions, through the organization of research seminars, workshops, and the dissemination of research done by members of the Center.

The Computational Optimization Research Center (CORC) at Columbia University is an interdisciplinary group of researchers from a variety of departments on the Columbia campus. Its permanent members are Professors Daniel Bienstock, Don Goldfarb, Garud Iyengar, Jay Sethuraman, and Cliff Stein, from the Industrial Engineering and Operations Research Department, and Professor David Bayer, from the Department of Mathematics at Barnard College. Researchers at CORC specialize in the design and implementation of state-of-the-art algorithms for the solution of large-scale optimization problems arising from a wide variety of industrial and commercial applications.

The FDT Center for Intelligent Asset Management is led by Professor Xunyu Zhou at Columbia University. The Center will focus on the exploration of theoretical underpinnings and modeling strategies for financial portfolio management through the introduction of big data analytical techniques. The Center's research will combine modern portfolio theory, behavioral finance, machine learning, and data science to study core problems including optimal asset allocation and risk management; and the research of the Center sits at the crossroads of financial engineering, computer science, statistics, and finance, aiming at providing innovative and intelligent investment solutions.

BACHELOR OF SCIENCE PROGRAMS

Industrial Engineering

The undergraduate program is designed to develop the technical skills and intellectual discipline needed by our graduates to become leaders in industrial engineering and related professions. The program is distinctive in its emphasis on quantitative, economic, computer-aided approaches to production and service management problems. It is focused on providing an experimental and mathematical problem-formulating and problem-solving framework for industrial engineering work. The curriculum provides a broad foundation in the current ideas, models, and methods of industrial engineering. It also includes a substantial component in the humanities and social sciences to help students understand the societal implications of their work.

The industrial engineering program objectives are:

1. To provide students with the requisite analytical and computational skills to assess practical situations and academic problems, formulate models of the problems represented or embedded therein, design potential solutions, and evaluate their impact;
2. To prepare students for the workplace by fostering their ability to participate in teams, understand and practice interpersonal and organizational behaviors, and communicate their solutions and recommendations effectively through written, oral, and electronic presentations;
3. To familiarize students with the historical development of industrial engineering tools and techniques and with the contemporary state of the art, and to instill the need for lifelong learning within their profession; and
4. To instill in our students an understanding of ethical issues and professional and managerial responsibilities.

Operations Research

The operations research program is one of several applied science programs offered at the School. At the undergraduate level, it offers basic courses in probability, statistics, applied mathematics, simulation, and optimization as well as more professionally oriented operations research courses. The curriculum is well suited for students with an aptitude for mathematics applications.

It prepares graduates for professional employment as operations research analysts, e.g., with management consultant and financial service organizations, as well as for graduate studies in operations research or business. It is flexible enough to be adapted to the needs of future medical and law students.

Operations Research: Engineering Management Systems

This operations research option is designed to provide students with

INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH PROGRAM[1]: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0)	Linear algebra (3)[2]
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	Chemistry or physics lab: PHYS UN1494 (3) **or** PHYS UN3081 (2) **or** CHEM UN1500 (3) **or** CHEM UN1507 (3) **or** CHEM UN3085 (4) **or**	
CHEMISTRY (choose one course)	UN1403 (3) **or** UN1404 (3) **or** UN1604 (3.5) **or** UN2045 (3.5)			
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL ELECTIVES	ECON UN1105 (4) **and** UN1155 recitation (0) either semester		HUMA CC1001, COCI CC1101, **or** Global core (3–4)	HUMA CC1002, COCI CC1102, **or** Global core (3–4)
			HUMA UN1121 **or** UN1123 (3) either semester	
FIRST- AND SECOND-YEAR DEPT. REQUIREMENTS			IEOR E3658 (3) either semester	
COMPUTER SCIENCE	ENGI E1006 (3) in either semester[3]			IEOR E2000(3)[4]
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] This includes all undergraduate programs within the Department of Industrial Engineering and Operations Research.

[2] The linear algebra requirement may be filled by either MATH UN2010 or APMA E3101 or COMS W3251.

[3] ENGI E1006 can be replaced by COMS W1004 or COMS W1007.

[4] IEOR E2000 can be replaced by COMS W3134 and COMS W4111. Students cannot get credit for IEOR E2000 if IEOR E2000 is taken after COMS W3134 and COMS W4111.

INDUSTRIAL ENGINEERING: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]		IEOR E3106 (3) Stochastic systems and applications IEOR E3608 (3) Foundations of optimization IEOR E4307 (3) Statistics and data analysis	IEOR E3402 (4) Production & inventory planning IEOR E3404 (4) Simulation IEOR E3609 (3) Advanced optimization	IEME E4200 (3) Human-centered design and innovation	IEOR E4405 (3) Scheduling
ELECTIVES	**NONTECH**	Students must complete the 27-point requirement. Please refer to page 9.			
	TECH[2]	15 points			
	MANAGEMENT[3]	3 points			
TOTAL ESTIMATED POINTS[4]		15	14	15	12

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

[2] 15 points total. At least 6 points need to be at least 3000 level with the prefix IEOR, ORCS, or CSOR. The complete list is available at ieor.columbia.edu/undergraduate/electives.

[3] 3 points total. Cannot double-count non-technical electives. The complete list is available at ieor.columbia.edu/undergraduate/electives.

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

OPERATIONS RESEARCH: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]		IEOR E3106 (3) Stochastic systems and applications IEOR E3608 (3) Foundation of optimization IEOR E4307 (3) Statistics and data analysis	IEOR E3402 (3) Production & inventory planning IEOR E3404 (4) Simulation IEOR E3609 (3) Advanced optimization	IEOR E4407 (3) Game theoretic models of operations	IEOR E4405 (3) Scheduling
ELECTIVES	NONTECH	Students must complete the 27-point requirement. Please refer to page 9.			
	TECH[2]	15 points			
	MANAGEMENT[3]	3 points			
TOTAL ESTIMATED POINTS[4]		15	14	15	12

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

[2] 15 points total. At least 6 points need to be at least 3000 level with the prefix IEOR, ORCS, or CSOR. The complete list is available at ieor.columbia.edu/undergraduate/electives.

[3] 3 points total. Cannot double-count non-technical electives. The complete list is available at ieor.columbia.edu/undergraduate/electives.

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

OPERATIONS RESEARCH: ANALYTICS: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]		IEOR E3106 (3) Stochastic systems and applications IEOR E3608 (3) Foundation of optimization IEOR E4307 (3) Statistics and data analysis IEOR E4212 (3) Data analytics & machine learning for OR	IEOR E3404 (4) Simulation IEOR E3609 (3) Advanced optimization IEOR E4650 (3) Business analytics ORCS E4201 (4) Policy for privacy technologies		
ELECTIVES	NONTECH	Students must complete the 27-point requirement. Please refer to page 9.			
	TECH[2]	15 points			
	MANAGEMENT[3]	3 points			
TOTAL ESTIMATED POINTS[4]		15	13	15	12

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

[2] 15 points total. At least 6 points need to be at least 3000 level with the prefix IEOR, ORCS, or CSOR. The complete list is available at ieor.columbia.edu/undergraduate/electives.

[3] 3 points total. Cannot double-count non-technical electives. The complete list is available at ieor.columbia.edu/undergraduate/electives.

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

OPERATIONS RESEARCH: ENGINEERING MANAGEMENT SYSTEMS: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]		IEOR E3106 (3) Stochastic systems and applications IEOR E3608 (3) Foundations of optimization IEOR E4307 (3) Statistics and data analysis	IEOR E3402 (4) Production & inventory planning IEOR E3404 (4) Simulation IEOR E3609 (3) Advanced optimization	IEOR E4003 (3) Corporate finance for eng.	IEOR E4998 (4) Managing technological innovations
ELECTIVES	**NONTECH**	Students must complete the 27-point requirement. Please refer to page 9.			
	TECH[2]	12 points			
	MANAGEMENT[3]	6 points			
TOTAL ESTIMATED POINTS[4]		15	14	15	12

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

[2] 12 points total. At least 6 points need to be at least 3000 level with the prefix IEOR, ORCS, or CSOR. The complete list is available at ieor.columbia.edu/undergraduate/electives.

[3] 6 points total. Cannot double-count non-technical electives. The complete list is available at ieor.columbia.edu/undergraduate/electives.

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

OPERATIONS RESEARCH: FINANCIAL ENGINEERING: THIRD AND FOURTH YEARS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES[1]		IEOR E3106 (3) Stochastic systems and applications IEOR E3608 (3) Foundations of optimization IEOR E4003 (3) Corporate finance for eng IEOR E4307 (3) Statistics and data analysis	IEOR E3404 (4) Simulation IEOR E3609 (3) Advanced optimization IEOR E4700 (3) Intro. to FE	IEOR E4500 (3) Applications prog. for FE	
ELECTIVES	**NONTECH**	Students must complete the 27-point requirement. Please refer to page 9.			
	TECH[2]	15 points			
	MANAGEMENT[3]	3 points			
TOTAL ESTIMATED POINTS[4]		15	13	15	12

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

[2] 15 points total. At least 6 points need to be at least 3000 level with the prefix IEOR, ORCS, or CSOR. The complete list is available at ieor.columbia.edu/undergraduate/electives.

[3] 3 points total. Cannot double-count non-technical electives. The complete list is available at ieor.columbia.edu/undergraduate/electives.

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

an understanding of contemporary technology and management. It is for students who are interested in a technical-management background rather than one in a traditional engineering field. It consists of required courses in industrial engineering and operations research, economics, business, and computer science, intended to provide a foundation for dealing with engineering and management systems problems. Elective courses are generally intended to provide a substantive core in at least one technology area and at least one management area.

Due to the flexibility of this option, it can incorporate the varied educational needs of preprofessional students interested in law, medicine, business, and finance. In addition, most students are encouraged to add a minor in economics or computer science to their standard course schedules.

Operations Research: Analytics

The analytics concentration within the operations research program seeks to train students to leverage advanced quantitative models, algorithms, and data for making actionable decisions to improve business operations. Examples include staffing and scheduling at hospitals, ride matching and pricing for on-demand car services, personalized promotions in online retail, and smarter energy consumption. Students are provided with a rigorous exposure to optimization and stochastic modeling, as well as machine learning and data analysis tools for predictive modeling and prescriptive analytics. Electives in the areas of healthcare, marketing, transportation, deep learning, and many others further enrich students with domain expertise, and provide many opportunities to work directly with data on real-world problems.

Operations Research: Financial Engineering

The operations research concentration in financial engineering is designed to provide students with an understanding of the application of engineering methodologies and quantitative methods to finance. Financial engineering is a multidisciplinary field integrating financial theory with economics, methods of engineering, tools of mathematics, and practice of programming. Students graduating with this concentration are prepared to enter careers in securities, banking, financial management, and consulting industries, and fill quantitative roles in corporate treasury and finance departments of general manufacturing and service firms.

Students who are interested in pursuing the rigorous concentration in financial engineering must demonstrate proficiency in calculus, computer programming, linear algebra, ordinary differential equations, probability, and statistics.

Undergraduate Advanced Track

The undergraduate advanced track is designed for advanced undergraduate students with the desire to pursue further higher education after graduation. Students with a minimum cumulative GPA of 3.4 and faculty approval have the opportunity to participate. Students are invited to apply to the track upon the completion of their sophomore year. Advanced track students are required to take higher-level IEOR courses, including the following:

Foundations of Research (3 credits):

IEOR E3700: Research immersion in OR and data analytics

In addition, we recommend students take Proof Writing Workshop held by Math Department (0 credits)

Advanced Course Requirement (6 credits):

MATH GU4061: Intro to Modern Analysis I
MATH GU4062: Intro to Modern Analysis II
MATH GU4041: Intro to Modern Algebra I
MATH GU4042: Intro to Modern Algebra II
IEOR E6613: Optimization, I
IEOR E6614: Optimization, II
IEOR E6711: Stochastic Modeling, I
IEOR E6712: Stochastic Modeling, II
IEOR E4008: Computational Discrete Optimization
APAM E4300: Intro to Numerical Methods
APMA E4200: Partial Differential Equations
CSOR E4231: Analysis of Algorithms

Research Project (3 credits):

IEOR E3900: Undergrad Research

Students successfully completing the requirements of the undergraduate advanced track will receive recognition on their academic record.

Minors

A number of minors are available for students wishing to add them to their programs. These minors are described starting on page 208 of this bulletin.

IEOR program students may want to consider minors in economics or computer science. In addition, operations research and engineering and management systems majors may elect to minor in industrial engineering, and industrial engineering majors may elect to minor in operations research.

The department does not offer a minor in engineering management systems or financial engineering.

GRADUATE PROGRAMS

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

MASTER OF SCIENCE PROGRAMS

The Department of Industrial Engineering and Operations Research offers courses and M.S. programs in (1) financial engineering on a full-time basis only; (2) management science and engineering on a full-time basis only; (3) business analytics on a full-time basis only; (4) industrial engineering on either a full- or part-time basis; and (5) operations research on either a full- or part-time basis. Both the Department's M.S. programs in Business Analytics and Management Science and Engineering are offered in conjunction with Columbia Business School. Lastly, the Department and Columbia Business School offer a combined M.S./M.B.A. degree program in industrial engineering.

All degree program applicants are required to take the Aptitude Tests of the Graduate Record Examination (GRE). M.S./M.B.A. candidates are also required to take the Graduate Management Admissions Test (GMAT). A minimum grade-point average of 3.0 (B) or its equivalent in an undergraduate engineering program is required for admission to the M.S. programs. At a minimum, students are expected, on entry, to have completed courses in ordinary differential equations, linear algebra, probability, and a programming language such as C, Java, or Python.

The Department requires that M.S. students achieve grades of B– or higher in each of the fundamental core courses in the discipline of study. Poor performance in core courses is indicative of inadequate preparation and is very likely to lead to serious problems in completing the program. As a result, students failing to meet this criterion 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 (e.g., courses with the following prefixes: ACTU, BUSI, COPR, IKNS, SUMA, FUND, and more). Please 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 interactions 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 to improve business operations. Students pursuing this degree program are provided with rigorous exposure to optimization and stochastic modeling, and a deep coverage of applications in the areas of analytics. The role of analytics has grown increasingly critical in business, health care, government, and many other sectors of the economy.

It is a 36-credit degree STEM-designated program (equivalent of 12 three-credit courses), assuming adequate preparation in probability and statistics, with students taking at least six courses (18 credits) within the IEOR Department, and four to six courses (12–18 credits) at the Business School. The remaining courses, if any, can be taken

Business Analytics (36 points)	
Required Core Courses (18 points)	**IEOR E4004** Optimization models and methods (first fall semester) **IEOR E4101** Probability, statistics and simulation (first fall semester) **IEOR E4502** Python for analytics (0 pt) (first fall semester) **IEOR E4523** Data analytics (fall semester) **ENGI E4000** Professional development (0 pt) (first fall semester, year long) **IEOR E4650** Business analytics (spring semester) **IEOR E4524** Analytics in practice (spring semester) **IEOR E4599** MSBA quantitative bootcamp (0 pt) **MRKT B9651** Marketing analytics (first fall semester)
Concentration Courses (Financial Analytics & Financial Technology (FinTech), Marketing Analytics, Healthcare Analytics, and Analytics Algorithms & Methodology)	
Financial Analytics & Financial Technology (FinTech) (9 points)	**IEOR E4106** Stochastic models **IEOR E4500** Applications programming for Financial Engineering **IEOR E4525** Machine learning for FE & OR **IEOR E4574** Technology innovation in financial services (1.5) **IEOR E4742** Deep learning for FE & OR **IEOR E4725** Big data in finance **MRKT B8649** Pricing strategies **DROM B8106** Operations strategy **DROM B8116** Risk management **DROM/MGMT B8510** Managerial negotiations **MRKT B8776** Foundations of innovation **DROM B8816** Quantitative pricing and revenue analytics **DROM B9122** Computing for business research
Marketing Analytics (9 points)	**IEOR E4407** Game theoretic models of operations **IEOR E4506** Designing digital operating models **IEOR E4312** Application of OR & AI techniques in marketing (1.5) **IEOR E4562** Innovate using design thinking (Blockweek) **IEOR E4601** Dynamic pricing and revenue management **DROM B8122** Game-theoretic business strategy **DROM B8123** Demand and supply analytics **DROM B8131** Sports analytics **DROM/MRKT B8510** Managerial negotiations **MRKT B8607** Strategic consumer insights **MRKT B8608** New product development **MRKT B8617** Marketing research and analytics **MRKT B8623** Intro to product management (1.5) **MRKT B8625** Winning strategic capabilities **MRKT B8679** Digital marketing **MRKT B8681** Advanced marketing strategy **MRKT B8683** Marketing models **DROM B9122** Computing for business research **DROM B9127** Online marketplaces **MRKT B9613** Mathematical models in marketing **MRKT B9656** Customer management: concepts and tools (1.5)
Healthcare Analytics (9 points)	**IEOR E4108/DROM 8108** Supply chain analytics **IEOR E4405** Scheduling **IEOR E4505** Operations research in public policy **IEOR E4507** Health care operations management **IEOR E4520** Applied systems engineering **IEOR E4521** Systems engineering tools and methods (OR) **IEOR E4540** Data mining for engineers **DROM B8105** Healthcare analytics (1.5) **DROM B8107** Service operations **DROM B8128** Healthcare investment and entrepreneurship HCIT and services **DROM B8132** Digital health care systems **DROM/MGMT B8510** Managerial negotiations **MRKT B8692** Pharmaceutical drug commercialization: strategy & practice (1.5) **DROM B8832** U.S. health care system **MRKT B9656** Customer management: concepts and tools (1.5)
Analytics Algorithms & Methodology (9 points)	**IEOR E4008** Computational discrete optimization **COMS W4111** Introduction to databases **CSOR W4231** Analysis of algorithms **IEOR E4407** Game theoretic models of operations **IEOR E4418** Transportation analytics & logistics **IEOR E4525** Machine learning for FE & OR **IEOR E4526** Analytics on the cloud **IEOR E4540** Data mining for engineers **DROM B8110** Business analytics strategy **DROM B8111** Analytics for business research **DROM B8127** Big immersion seminar—big data (1.5 pts) **DROM B8130** Applied statistics and data analytics **MRKT B9160** Applied multivariate statistics **MRKT B9608** Experimental design & analysis for behavioral research **MRKT B9616** Bayesian modeling & computation **MRKT B9652** MS marketing models **MRKT B9653** MS machine learning (1.5) **MRKT B9654** MS artificial intelligence

at the School of Engineering, the School of International and Public Affairs, the Law School, or the Departments of Economics, Mathematics, and Statistics. Additional details are available on the MSBA website at msba.engineering.columbia.edu/content/curriculum.

Financial Engineering

The M.S. program in Financial Engineering is offered on a full time basis only. Financial Engineering is intended to provide a unique technical background for students interested in pursuing career opportunities in financial analysis and risk management. In addition to the basic requirements for graduate study, students are expected, on entry, to have attained a high level of mathematical and computer programming skills, particularly in probability, statistics, linear algebra, and the use of a programming language such as C, Python or JAVA. Previous professional experience is highly desirable but not required.

Graduate studies in Financial Engineering consists of 36 points (12 courses), starting the fall semester. Students may complete the program in May, August, or December of the following year. The requirements include six required core courses and additional elective courses chosen from a variety of departments or schools at Columbia. The six required core courses for Financial Engineering are IEOR E4007, E4701, E4703, E4706, E4707, and E4709. In addition, students are required to attend IEOR E4798 Financial Engineering Seminar and submit learning journals.

Financial Engineering has seven concentrations: (1) Asset Management; (2) Computation and Programming; (3) Computational Finance and Trading Systems; (4) Derivatives; (5) Finance and Economics; (6) Financial Technology; and (7) Machine Learning for Financial Engineering. A sample schedule is available in the Department office and on the IEOR website at ieor.columbia.edu. Students select electives from a group of specialized offerings in both the fall and spring terms. They may select from a variety of approved electives from the Department, Columbia Business School, and the Graduate School of Arts and Sciences.

Financial Engineering (36 points)[1]	
Fall Semester (9 points)[2]	Required core courses: **IEOR E4007** Optimization models and methods **IEOR E4701** Stochastic models **IEOR E4706** Foundations of financial engineering **IEOR E4798** Financial engineering seminar (0 pt) **IEOR E4799** MSFE quantitative & computational bootcamp (0 pt) Plus Financial Engineering electives, 3–6 points [3]
Spring Semester (9 points)[2]	Required core courses: **IEOR E4703** Monte Carlo simulation **IEOR E4707** Continuous time finance **IEOR E4709** Statistical analysis and time series Plus Financial Engineering electives, 3–6 points [3]
Summer and/or Fall Semester (For remaining credits)[2]	**CSOR W4231** Analysis of algorithms I **IEOR E4311** Derivatives marketing & structuring (1.5) **IEOR E4500** Applications programming for financial engineers **IEOR E4525** Machine learning for FE & OR **IEOR E4602** Quantitative risk management **IEOR E4630** Asset allocation **IEOR E4710** Term structure modeling **IEOR E4718** Beyond Black-Scholes: the implied volatility smile **IEOR E4722** Stochastic control & financial applications **IEOR E4723** Blockchain & cryptocurrency investing (1.5) **IEOR E4726** Applied financial risk management **IEOR E4729** Algorithmic trading **IEOR E4731** Credit risk modeling and derivatives **IEOR E4732** Computational methods in finance **IEOR E4734** Foreign exchange and related derivatives instruments (1.5) **IEOR E4735** Introduction to structured and hybrid products **IEOR E4741** Programming for financial engineering **IEOR E4742** Deep learning for OR & FE Additional Financial Engineering electives will be offered [3]

[1] Students may conclude the program in May, August, or December. Please visit the departmental website at msfe.ieor.columbia.edu for more information.

[2] All courses listed are for 3 points, unless stated otherwise.

[3] The list of Financial Engineering electives can be found at ieor.columbia.edu/masters-financial-engineering/curriculum.

Management Science and Engineering

Management Science and Engineering (MS&E), offered by the IEOR Department in partnership with Columbia Business School, is the first such program between Columbia Engineering and Columbia Business School. It reflects the next logical step in the long-standing close collaboration between the IEOR Department at the Engineering School and the Decision, Risk, and Operations (DRO) Division at the Business School. Coursework emphasizes both management and engineering perspectives in solving problems, making decisions, and managing risks in complex systems. Students pursuing this specialization are provided with a rigorous exposure to optimization and stochastic modeling, and a deep coverage of applications in the areas of operations engineering and management.

In addition to the core and semi-core requirements, Management Science and Engineering has seven concentrations: (1) Operations and Analytics; (2) Pricing and Revenue Management; (3) Entrepreneurship and Innovation; (4) Logistics and Supply Chain Management; (5) Financial Technology (Fin Tech); (6) Healthcare Management and; (7) Product Management. Additional details regarding these concentrations are available on the MS&E website at ieor.columbia.edu/mse-curriculum.

Graduates of this program are expected to assume positions as analysts and associates in consulting firms, business analysts in logistics, supply chain, operations, or revenue management departments of large corporations, and as financial analysts in various functions (e.g., risk management) of investment banks, hedge funds, credit-card companies, and insurance firms.

Management Science and Engineering (36 points)	
Required Core Courses (12 points)	**IEOR E4004** Optimization models and methods (first fall semester) **IEOR E4101** Probability, statistics, and simulation (first fall semester) **IEOR E4102** Stochastic models (spring semester) **IEOR E4111** Operations consulting (starts first fall semester, year-long course) **DROM B8000** Optimization and simulation bootcamp (0 pt)
Semi-Core Courses (DRO, Analysis, and Management Electives 18 points)	
Decision, Risk, and Operations Electives (9 points)	**IEOR E4650** Business analysis **DROM B8101** Business analytics II (1.5 pt) **DROM B8105** Healthcare analytics (1.5) **DROM B8106** Operations strategy (1.5 pt) **DROM B8107** Service operations **DROM B8110** Business analytics strategy **DROM B8116** Risk management **DROM B8123** Demand & supply analytics **DROM B8131** Sports analytics **DROM B8510** Managerial negotiations
Analysis and Management Electives (9 points minimum)	
Analysis Group *At least one of the following:*	**IEOR E4008** Computational discrete optimization **CSOR W4231** Analysis of algorithms I **IEOR E4405** Scheduling **IEOR E4407** Game theoretic models of operations **IEOR E4418** Transportation analytics and logistics **IEOR E4501** Tools for analytics **IEOR E4507** Healthcare operations management **IEOR E4523** Data analytics **IEOR E4525** Machine learning for financial engineering & operations research **IEOR E4526** Analytics on the cloud **IEOR E4540** Data mining for engineering **IEOR E4532** Visualization & storytelling with data (1.5) **IEOR E4533** Performance, objectives & results using data analytics (1.5) **IEOR E4601** Dynamic pricing and revenue optimization **IEOR E4742** Deep learning for operations research & financial engineering **DROM B8108** Supply chain analytics
Management Group *At least one of the following:*	**IEOR E4412** Quality control and management **IEOR E4505** Operations research in public policy **IEOR E4506** Designing digital operating models **IEOR E4510** Project management **IEOR E4550** Entrepreneurial business creation for engineers **IEOR E4561** Launch your startup: tech **IEOR E4562** Innovate using design thinking (weeklong course in mid-January, by application only) **IEOR E4570** Entrepreneurship bootcamp for engineers (2-day long course fall or spring semester, by application only) **IEOR E4711** Global capital markets **IEOR E4998** Managing technological innovation and entrepreneurship
Breadth Electives: The breadth electives can be selected from the Business School, the School of Engineering, the School of International and Public Affairs, the Law School, or the Departments of Economics, Mathematics, and Statistics.	

Management Science and Engineering (36 points) can be completed in a single calendar year, in three semesters. Students enter in the fall term and can either finish their coursework at the end of the following August, or alternatively, have the option to take the summer term off (e.g., for an internship) and complete their coursework by the end of the following fall term. Students are required to take the equivalent of 12 3-point courses (36 points).

Students must take at least six courses (18 points) within the IEOR Department, three to six courses at the Business School, and the remaining courses (if any) within the School of Engineering; the School of International and Public Affairs; the Law School; or the Departments of Economics, Mathematics, and Statistics. Students in residence during the summer term can take two to four Business School courses in the third (summer) semester in order to complete their program. Additional details regarding these electives are available in the Departmental office and on the MS&E website at mse.ieor.columbia.edu.

Industrial Engineering

Graduate studies in Industrial Engineering enable students with industrial engineering bachelor's degrees to enhance their undergraduate training with studies in special fields such as production planning, inventory control, scheduling, and industrial economics. However, the department also offers a broader master's program for engineers whose undergraduate training is not in industrial engineering. Students may complete the studies on a full-time (12 points per term) or part-time basis.

Industrial Engineers are required to satisfy a core program of graduate courses in production management, probability theory, statistics, simulation, and operations research. Students with B.S. degrees in industrial engineering will usually have satisfied this core in their undergraduate programs. All students must take at least 18 points of graduate work in industrial engineering and at least 30 points of graduate studies at Columbia. Industrial Engineering may include concentrations in: (1) Healthcare

Operations Research (30 points)		
Required Core Courses (12 points)	**IEOR E4150** Intro to probability and statistics (or **STAT GU4001** for spring intake only)[1] **IEOR E4004** Optimization models and methods **IEOR E4106** Stochastic models **IEOR E4404** Simulation	
Concentrations The department recommends taking three to five elective courses, depending on the concentration.	**Analytics** **Entrepreneurship and Innovation** **Finance and Management** **Healthcare Management**	**Logistics and Supply Chain Management** **Machine Learning and Artificial Intelligence** **Optimization** **Stochastic Modeling**

[1] STAT GU4001 will not count toward the 18 IEOR point requirement.

Management; (2) Regulated Industries; and (3) Systems Engineering. Additional details regarding these concentrations and electives are available in the Departmental office and on the IEOR website at ieor.columbia.edu.

Operations Research

Graduate studies in Operations Research enables students to concentrate their studies in methodological areas such as mathematical programming, stochastic models, and simulation. Students may complete the studies on a full time (12 points per term) or part time basis.

Operations Research has eight areas of concentrations, including: (1) Analytics; (2) Stochastic Modeling; (3) Entrepreneurship and Innovation; (4) Finance and Management; (5) Healthcare Management; (6) Logistics and Supply Chain Management; (7) Machine Learning and Artificial Intelligence; and (8) Optimization. Students may select from a variety of approved electives from the Department, Columbia Business School, and the Graduate School of Arts and Sciences. Additional details regarding these concentrations and electives are available in the Departmental office and on IEOR's website at ieor.columbia.edu.

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

The Department and Columbia Business School offer a joint M.S. program in Industrial Engineering. Prospective students for this special program must submit separate applications to Columbia Engineering and Columbia Business School and be admitted to both schools for entrance into the joint program.

Admissions requirements are the same as those for the regular M.S. program in Industrial Engineering and for the M.B.A. This joint program is coordinated so that both degrees can be obtained after five terms of full-time study (30 points in two terms while registered in Columbia Engineering and 45 points in three terms while registered in Columbia Business School).

Students in the joint program must complete certain courses by the end of their first year of study. If a substantial equivalent has been completed during undergraduate studies, students should consult with a faculty adviser in order to obtain exemption from a required course.

PH.D. PROGRAM

The IEOR Department offers two Ph.D. programs in (1) Industrial Engineering; and (2) Operations Research. The requirements for the Ph.D. in industrial engineering and operations research are identical. Both programs require the student to complete the qualifying procedure and submit and defend a dissertation based on the candidate's original research, conducted under the supervision of the faculty. The dissertation work may be theoretical or computational or both.

The qualifying procedure consists of three components, including: (1) complete the four core courses during the first year with an average grade of (A-) or above; (2) conduct research during the first summer (ideally starting in Spring or earlier) and present it in a department seminar at the beginning of the third semester; and (3) submit a research report (paper) at the end of the third semester. Students will be reviewed after each component. A student who fails to complete component (1) may be asked to withdraw from the program at the end of the first year.

A student who successfully completes component (1) will typically move on to do summer research, advised by a faculty member in the IEOR Department. In the rare instance the Ph.D. committee is dissatisfied with a student's performance in components (2) and (3), they may be asked to withdraw from the program at the end of the second year.

Doctoral students are also required to take 4 additional Ph.D. courses (possibly in other departments) during the course of the Ph.D. Research credits (IEOR E9101) do not count toward this requirement. It is important to select courses you find interesting while considering your background and in consultation with your academic adviser. Students can consider courses from other departments including Mathematics, Computer Science, Statistics, Economics, and Decision Risk and Operations. Doctoral candidates must obtain a minimum of 60 points of formal course credit beyond the bachelor’s degree. A master’s degree from an accredited institution may be accepted as equivalent to 30 points. A minimum of 30 points beyond the master’s degree must be earned while in residence in the doctoral program. Detailed information regarding the requirements for the doctoral degree may be obtained in the Department office and on the IEOR website at ieor.columbia.edu.

COURSES IN INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

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

IEOR E1000x or y Frontiers in operations research and data analytics
1 pt. Lect: 1.
Introductory course for overview of modern approaches and ideas of operations research and data analytics. Through a series of interactive sessions, students engage in activities exploring OR topics with various faculty members from the IEOR department.

IEOR E2000y Data engineering with Python
3 pts. Lect: 3. Professor Zhang.
Prerequisite(s): ENGI E1006 or competency in Python. Introduction to essential data engineering methods. Potential topics include Arrays, Linked Lists, Stacks and Queues, Trees and Graphs, Hash Tables, Search Algorithms and Efficiency, Relational databases, SQL, NoSQL, and Data Wrangling. Practice both theory and applications using Python programming.

IEOR E2261x and y Accounting and finance
3 pts. Lect: 3.
Prerequisite(s): ECON UN1105 Principles of economics. For undergraduates only. Examines the fundamental concepts of financial accounting and finance, from the perspective of both managers and investors. Key topics covered include principles of accrual accounting; recognizing and recording accounting transactions; preparation and analysis of financial statements; ratio analysis; pro-forma projections; time value of money (present values, future values and interest/discount rates); inflation; discounted-cash-flow (DCF) project evaluation methods; deterministic and probabilistic measures of risk; capital budgeting.

ORCA E2500y Foundations of data science
3 pts. Lect: 3.
Prerequisite(s): MATH UN1101 and UN1102. Some familiarity with programming. Designed to provide an introduction to data science for sophomore SEAS majors. Combines three perspectives: inferential thinking, computational thinking, and real-world applications. Given data arising from some real-world phenomenon, how does one analyze that data so as to understand that phenomenon? Teaches critical concepts and skills in computer programming, statistical inference, and machine learning, in conjunction with hands-on analysis of real-world datasets such as economic data, document collections, geographical data, and social networks. At least one project will address a problem relevant to New York City.

IEOR E3106x Stochastic systems and applications
3 pts. Lect: 3.
Prerequisite(s): IEOR E3658. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Must be taken during (or before) the fifth semester. Some of the main stochastic models used in engineering and operations research applications: discrete-time Markov chains, Poisson processes, birth and death processes and other continuous Markov chains, renewal reward processes. Applications: queueing, reliability, inventory, and finance. IEOR E3106 must be completed by the fifth term. Only students with special academic circumstances may be allowed to take these courses in alternative semesters with the consultation of CSA and Departmental advisers.

IEOR E3402y Production and inventory planning
4 pts. Lect: 3. Recit: 1.
Prerequisite(s): IEOR E3608 and E3658. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Must be taken during (or before) the sixth semester. Inventory management and production planning. Continuous and periodic review models: optimal policies and heuristic solutions, deterministic and probabilistic demands. Material requirements planning. Aggregate planning of production, inventory, and work force. Multi-echelon integrated production-inventory systems. Production scheduling. Term project. Recitation section required.

IEOR E3404y Simulation modeling and analysis
4 pts. Lect: 4.
Prerequisite(s): IEOR E3658 and E4307 or STAT GU4001, and knowledge of a programming language such as Python, C, C++ or Matlab. It is strongly advised that Stochastic modeling (IEOR E3106 or IEOR E4106) be taken before this course. This is an introductory course to simulation, a statistical sampling technique that uses the power of computers to study complex stochastic systems when analytical or numerical techniques do not suffice. The course focuses on discrete-event simulation, a general technique used to analyze a model over time and determine the relevant quantities of interest. Topics covered in the course include the generation of random numbers, sampling from given distributions, simulation of discrete-event systems, output analysis, variance reduction techniques, goodness of fit tests, and the selection of input distributions. The first half of the course is oriented toward the design and implementation of algorithms, while the second half is more theoretical in nature and relies heavily on material covered in prior probability courses. The teaching methodology consists of lectures, recitations, weekly homework, and both in-class and take-home exams. Homework almost always includes a programming component for which students are encouraged to work in teams.

IEOR E3608x Foundations of optimization
3 pts. Lect: 3.
Prerequisite(s): MATH UN2010 and data structures. This first course in optimization focuses on theory and applications of linear optimization, network optimization, and dynamic programming.

IEOR E3609y Advanced optimization
3 pts. Lect: 3.
Prerequisite(s): IEOR E3608. For undergraduates only. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. This is a follow-up to IEOR E3608 and will cover advanced topics in optimization, including integer optimization, convex optimization, and optimization under uncertainty, with a strong focus on modeling, formulations, and applications.

IEOR E3658x and y Probability for engineers
3 pts. Lect: 3.
Prerequisite(s): Calculus. For undergraduates only. Required for OR:FE concentration. Must be taken during or before third semester. Students who take IEOR E3658 may not take W4150 due to significant overlap. Recommended: strong mathematical skills. Introductory course to probability theory and does not assume any prior knowledge of subject. Teaches foundations required to use probability in applications, but course itself is theoretical in nature. Basic definitions and axioms of probability and notions of independence and conditional probability introduced. Focus on random variables, both continuous and discrete, and covers topics of expectation, variance, conditional distributions, conditional expectation and variance, and moment generating functions. Also Central Limit Theorem for sums of random variables. Consists of lectures, recitations, weekly homework, and in-class exams.

IEOR E3700y Research immersion in OR and data analytics
3 pts. Lect: 3. Professor Balkanski.
Prerequisite(s): IEOR E3658, IEOR E360, and IEOR E430. An overview of active research areas in Operations Research and Data Analytics, and an introduction to the essential components of research studies. This course helps students develop fundamental research skills, including paper reading, problem formulation, problem-solving, scientific writing, and research presentation. Classes are in seminar format, with students analyzing research papers, developing research projects, and presenting research findings.

IEOR E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

IEOR E3900x and y Undergraduate research or project
1–3 pts. Members of the faculty.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. Independent work involving experiments, computer programming, analytical investigation, or engineering design.

IEOR E3999x, y or s Fieldwork
1–1.5 pts. (up to 2 pts, summer only)
Prerequisite(s): Obtained internship and approval from faculty adviser. Only for IEOR undergraduate students who need relevant work experience as part of their program of study. Final reports are required. May not be taken for pass/fail credit or audited.

IEOR E4003x Corporate finance for engineers
3 pts. Lect: 3.
Prerequisite(s) or corequisites: Probability theory and linear programming. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Introduction to the economic evaluation

of industrial projects. Economic equivalence and criteria. Deterministic approaches to economic analysis. Multiple projects and constraints. Analysis and choice under risk and uncertainty.

IEOR E4004x and y Optimization models and methods
3 pts. Lect: 3.
A graduate course only for MS&E, IE, and OR students. This is also required for students in the Undergraduate Advanced Track. For students who have not studied linear programming. Some of the main methods used in IEOR applications involving deterministic models: linear programming, the simplex method, nonlinear, integer and dynamic programming.

IEOR E4007x Optimization models and methods for financial engineering
3 pts. Lect: 3.
Prerequisite(s): Linear algebra. This graduate course is only for M.S. Program in Financial Engineering students. Linear, quadratic, nonlinear, dynamic, and stochastic programming. Some discrete optimization techniques will also be introduced. The theory underlying the various optimization methods is covered. The emphasis is on modeling and the choice of appropriate optimization methods. Applications from financial engineering are discussed.

IEOR E4008x or y Computational discrete optimization
3 pts. Lect: 3.
Prerequisite(s): Linear programming, basic probability theory. Discrete optimization problems. Mathematical techniques and testing strengths and limits in practice on relevant applications. Transportation (travelling salesman and vehicle routing) and matching (online advertisement and school allocation) problems.

IEOR E4009x or y Nonlinear optimization
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): A course on optimization models and methods (at the level of IEOR E4004) and a course on linear algebra. Unconstrained and constrained nonlinear optimization involving continuous functions. Additionally, fundamental concepts such as optimality conditions and convergence, principle focus on practical optimization methods.

CSOR E4010y Graph theory: a combinatorial view
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Linear algebra, or instructor’s permission. An introductory course in graph theory with emphasis on its combinatorial aspects. Basic definitions, and some fundamental topics in graph theory and its applications. Topics include trees and forests graph coloring, connectivity, matching theory and others.

IEOR E4100x Statistics and simulation
1.5 pts. Lect: 1.5.
Prerequisite(s): Understanding of single- and multivariable calculus. Probability and simulation. Statistics building on knowledge in probability and simulation. Point and interval estimation, hypothesis testing, and regression. A specialized version of IEOR E4150 for MSE and MSBA students who are exempt from the first half of IEOR E4101. Must obtain waiver for E4101.

IEOR E4101x Probability, statistics and simulation
3 pts. Lect: 3.
Prerequisite(s): Understanding of single- and multivariable calculus. MSE and MSBA students only. Basic probability theory, including independence and conditioning, discrete and continuous random variable, law of large numbers, central limit theorem, and stochastic simulation, basic statistics, including point and interval estimation, hypothesis testing, and regression; examples from business applications such as inventory management, medical treatments, and finance. A specialized version of IEOR E4150 for MSE and MSBA students.

IEOR E4102y Stochastic models for MSE
3 pts. Lect: 3.
Prerequisite(s): IEOR E4101. Introduction to stochastic processes and models, with emphasis on applications to engineering and management; random walks, gambler’s ruin problem, Markov chains in both discrete and continuous time, Poisson processes, renewal processes, stopping times, Wald’s equation, binomial lattice model for pricing risky assets, simple option pricing; simulation of simple stochastic processes, Brownian motion, and geometric Brownian motion. A specialized version of IEOR E4106 for MSE students.

IEOR E4106x and y Stochastic models
3 pts. Lect: 3.
Prerequisite(s): STAT GU4001 or probability theory or IEOR E4150. This graduate course is only for IE and OR students. Also required for students in the Undergraduate Advanced Track. Some of the main stochastic models used in engineering and operations research applications: discrete-time Markov chains, Poisson processes, birth and death processes and other continuous Markov chains, renewal reward processes. Applications: queueing, reliability, inventory, and finance.

IEOR E4108/DROM B8108x or y Supply chain analytics
3 pts. Lect: 2.5.
Prerequisite(s): IEOR E3402 or instructor's permission. MS IEOR students only. Supply chain management, model design of a supply chain network, inventories, stock systems, commonly used inventory models, supply contracts, value of information and information sharing, risk pooling, design for postponement, managing product variety, information technology and supply chain management; international and environmental issues. Note: replaced IEOR E4000 beginning in fall 2018.

IEOR E4111x and y Operations consulting
3 pts. Lect: 3.
Prerequisite(s): Probability and statistics at the level of IEOR E3658 and E4307 or STAT GU4001, and Deterministic Models at the level of IEOR E3608 or IEOR E4004, or instructor permission. For MS-MS&E students only. Aims to develop and harness the modeling, analytical, and managerial skills of engineering students and apply them to improve the operations of both service and manufacturing firms. Structured as a hands-on laboratory in which students "learn by doing" on real-world consulting projects (October to May). The student teams focus on identifying, modeling, and testing (and sometimes implementing) operational improvements and innovations with high potential to enhance the profitability and/or achieve sustainable competitive advantage for their sponsor companies. The course is targeted toward students planning careers in technical consulting (including operations consulting) and management consulting, or pursuing positions as business analysts in operations, logistics, supply chain and revenue management functions, positions in general management, and future entrepreneurs.

IEOR E4150x Introduction to probability and statistics
3 pts. Lect: 3.
Prerequisite(s): Calculus, including multiple integration. Covers the following topics: fundamentals of probability theory and statistical inference used in engineering and applied science; Probabilistic models, random variables, useful distributions, expectations, law of large numbers, central limit theorem; Statistical inference: pint and confidence interval estimation, hypothesis tests, linear regression. For IEOR graduate students.

IEOR E4199y MSIEOR quantitative bootcamp
0 pt. Lect: 0.
Zero-credit course. Primer on quantitative and mathematical concepts. Required for all incoming MSOR and MSIE students.

IEME E4200x or y Human-centered design & innovation
3 pts. Lect: 2.5.
Prerequisite(s): Instructor's permission. Open to SEAS graduate and advanced undergraduate students, Business School, and GSAPP. Students from other schools may apply. Fast-paced introduction to human-centered design. Students learn the vocabulary of design methods, understanding of design process. Small group projects to create prototypes. Design of simple product, more complex systems of products and services, and design of business.

ORCS E4200y Data-driven decision modeling
3 pts. Lect: 3.
Introduction to modeling, estimating, and solving decision-making problems in the context of artificial intelligence and analytics. Potential topics include choice models, quantity models, online learning using multi-armed bandits, dynamic decision modeling, dynamic games, and Bayesian learning theory. Practice both theory and applications using Python programming.

ORCS E4201y Policy for Privacy Technologies
3 pts. Lect: 3. Professor Cummings
Introduction to privacy technologies, their use in practice, and privacy regulations. Potential topics include anonymization, differential privacy, cryptography, secure multi-party computation, and legislation. Course material will be abased in real-world use cases of these tools.

IEOR E4206x or y Intellectual property for engineers
0 pts. Not offered in 2024–2025.
Intellectual property (patents, copyrights, trademarks) are an increasingly critical part of almost any business, at almost any stage of growth. Provides the aspiring business executive, tech entrepreneur, or engineer with an overview of commercial opportunities and risks associated with intellectual property, with a particular focus on technology patents. While legal principles will be addressed, the primary focus is on leveraging intellectual property to create financial returns.

IEOR E4207x Human factors: performance
3 pts. Lect: 3.
Required for undergraduate students majoring in IE. Sensory and cognitive (brain) processing considerations in the design, development, and operations of systems, products, and tools. User or operator limits and potential in sensing, perceiving decision making, movement coordination, memory, and motivation.

IEOR E4208y Seminar in human factors design
3 pts. Lect: 3.
Prerequisite(s): IEOR E4207 or instructor’s permission. An elective for undergraduate students majoring in IE. An in-depth exploration of the application potential of human factor principles for the design of products and processes. Applications to industrial products, tools, layouts, workplaces, and computer displays. Consideration to environmental factors, training and documentation. Term project.

IEOR E4212x Data analytics and machine learning for OR
3 pts. Lect: 3.
Surveys tools available in Python for getting (web scraping and APIs) and visualizing data (charts and maps). Introduction to analytics through machine learning (ML algorithms, model evaluation, text analytics, network algorithms, deep learning).

IEOR E4307x Statistics and data analysis
3 pts. Lect: 3.
Prerequisite(s): probability, linear algebra. Descriptive statistics, central limit theorem, parameter estimation, sufficient statistics, hypothesis testing, regression, logistic regression, goodness-of-fit tests, applications to operations research models.

IEME E4310x The manufacturing enterprise
3 pts. Lect: 3. Not offered in 2024–2025.
The strategies and technologies of global manufacturing and service enterprises. Connections between the needs of a global enterprise, the technology and methodology needed for manufacturing and product development, and strategic planning as currently practiced in industry.

IEOR E4311x Derivatives marketing & structuring
1.5 pts. Lect: 1.5. Not offered in 2024–2025
Prerequisite(s): IEOR E3402, IEOR E4000, or instructor's permission. Covers topics in Accounting, relationships among different elements of financial statements, short- term and long-term financing alternatives, using swaps, cap, and floors to manage interest rate risk, hedging interest risk of corporate finance, using options as cheapeners, structured swaps, accounting treatment of derivatives, cash flow hedging, accrual accounting, hedging issuance of a bond using treasuries, hedging employee stock options, preferred shares and their use in corporate treasury, FX risk and FX translation, commodities hedging, operating lease vs capital lease, credit risk, and cred spread and funding. Note: restricted to IEOR MS students.

IEOR E4399y MSE quantitative bootcamp
0 pt. Lect: 0.
Zero-credit course. Primer on quantitative and mathematical concepts. Required for all incoming MSOR and MSIE students.

IEOR E4402x Corporate finance, accounting, & investment banking
3 pts. Lect: 3.
Prerequisite(s): Covers primary financial theories and alternative theories underlying Corporate Finance, such as CAPM, Miller Modigliani, Fama French factors, Smart Beta, etc. Interpret financial statements, build cash flow models, value projects, value companies, and make Corporate Finance decisions. Additional topics include: cost of capital, dividend policy, debt policy, impact of taxes, Shareholder/Debtholder agency costs, dual-class shares, using option pricing theory to analyze management behavior, investment banking activities, including equity underwriting, syndicated lending, venture capital, private equity investing and private equity secondaries. Application of theory in real-world situations: analyzing financial activities of companies such as General Electric, Google, Snapchat, Spotify, and Tesla.

IEOR E4403x Quantitative corporate finance
3 pts. Lect: 3.
Prerequisite(s): Probability theory and linear programming Required for students in the Undergraduate Advanced Track. Key measures and analytical tools to assess the financial performance of a firm and perform the economic evaluation of industrial projects. Deterministic mathematical programming models for capital budgeting. Concepts in utility theory, game theory and real options analysis.

IEOR E4404x and y Simulation
4 pts. Lect: 3. Recit: 1.
Prerequisite(s): IEOR E3658 and E4307 or STAT GU4001, computer programming. Corequisite(s): IEOR E3106 or IEOR E4106. Required for all undergraduate students majoring in IE, OR:EMS, OR:FE, and OR. Also required for MSOR. Generation of random numbers from given distributions; variance reduction; statistical output analysis; introduction to simulation languages; application to financial, telecommunications, computer, and production systems. Graduate students must register for 3 points. Undergraduate students must register for 4 points. Note: Students who have taken IEOR E4703 Monte Carlo simulation may not register for this course for credit. Recitation section required.

IEOR E4405y Scheduling
\3 pts. Lect: 3.
Prerequisite(s): IEOR E3608 and E3658. Computer programming. Required for undergraduate students majoring in IE and OR. Job shop scheduling: parallel machines, machines in series; arbitrary job shops. Algorithms, complexity, and worst-case analysis. Effects of randomness: machine breakdowns, random processing time. Term project.

IEOR E4407x Game theoretic models of operations
3 pts. Lect: 3.
Prerequisite(s): IEOR E4004 (or E3608), IEOR E4106 (or E3106), familiarity with differential equations and computer programming; or instructor’s permission. Required for undergraduate students majoring in OR:FE and OR. A mathematically rigorous study of game theory and auctions, and their application to operations management. Topics include introductory game theory, private value auction, revenue equivalence, mechanism design, optimal auction, multiple-unit auctions, combinatorial auctions, incentives, and supply chain coordination with contracts. No previous knowledge of game theory is required.

IEOR E4408x Resource allocation: models, algorithms, and applications
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Linear programming (IEOR E3608 or E4004), basic knowledge of nonlinear and integer programming. Overview of resource allocation models. Single resource allocation with concave returns; equitable resource allocation; lexicographic minmax/maxmin optimization; extensions to substitutable resources; multiperiod resource allocation; equitable allocation in multicommodity network flow models; equitable content distribution in networks; equitable resource allocation with discrete decision variables.

IEOR E4412y Quality control and management
3 pts. Lect: 3.
Prerequisite(s): IEOR E3658 and working knowledge of statistics. Required for undergraduate students majoring in IE. Statistical methods for quality control and improvement: graphical methods, introduction to experimental design and reliability engineering and the relationships between quality and productivity. Contemporary methods used by manufacturing and service organizations in product and process design, production and delivery of products and services.

IEOR E4418x or y Transportation analytics and logistics
3 pts. Lect: 3.
Prerequisite(s): IEOR E3608 or E4404 or permission of instructor. Introduces quantitative techniques and state-of-the-art practice of operations research relevant to the design and both the tactical and strategic management of logistical and transportation systems. Discusses a wide variety of passenger and freight systems, including air, urban and highway traffic, rail, and maritime systems. Explores the practice of revenue management and dynamic pricing. Through case studies, analyzes successes and failures in third-party

logistics, postal, truck and rail pickup and delivery systems. Investigates large-scale integrated logistics and transportation systems and studies the underlying principles governing transportation planning, investment and operations.

IEOR E4500x Applications programming for financial engineering
3 pts. Lect: 3.
Prerequisite(s): Computer programming or instructor's approval. Required for undergraduate students majoring in OR:FE. We will take a hands-on approach to developing computer applications for Financial Engineering. Special focus will be placed on high-performance numerical applications that interact with a graphical interface. In the course of developing such applications we will learn how to create DLLs, how to integrate VBA with C/C++ programs, and how to write multithreaded programs. Examples of problems settings that we consider include simulation of stock price evolution, tracking, evaluation and optimization of a stock portfolio; optimal trade execution. In the course of developing these applications, we review topics of interest to OR:FE in a holistic fashion.

ORCA E4500x or y Foundations of data science
3 pts. Lect: 3.
Prerequisite(s): MATH UN1101 and UN1102, some familiarity with programming. Designed to provide an introduction to data science for sophomore SEAS majors. Combines three perspectives: inferential thinking, computational thinking, and real-world applications. Given data arising from some real-world phenomenon, how does one analyze that data so as to understand that phenomenon? Teaches critical concepts and skills in computer programming, statistical inference, and machine learning, in conjunction with hands-on analysis of real-world datasets such as economic data, document collections, geographical data, and social networks.

IEOR E4501x and y Tools for analytics
3 pts. Lect: 3.
MS IEOR students only. Introduction programming in Python, tools with the programmer's ecosystem. Python, Data Analysis tools in Python (NumPy, pandas, bokeh), GIT, Bash, SQL, VIM, Linux/Debia, SSH.

IEOR E4502x Python for analytics
0 pts. Lect: 1.
Zero-credit course. Primer on Python for analytics concepts. Required for MSBA students.

IEOR E4505y Operations research in public policy
3 pts. Lect: 3.
Prerequisite(s): IEOR E3608 or IEOR E4004, IEOR E3106 or IEOR E4106. Aims to give the student a broad overview of the role of Operations Research in public policy. The specific areas covered include voting theory, apportionment, deployment of emergency units, location of hazardous facilities, health care, organ allocation, management of natural resources, energy policy, and aviation security. Draws on a variety techniques such as linear and integer programming, statistical and probabilistic methods, decision analysis, risk analysis, and analysis and control of dynamic systems.

IEOR E4506x Designing digital operating models
3 pts. Lect: 3.
IEOR students only. Understand digital businesses, apply scientific, engineering thinking to digital economy. Data-driven digital strategies and operating models. Sectors: ecommerce, advertising technology, and marketing technology. Automation of the marketing, sales, and advertising functions. Algorithms, patents, and business models. Business side of the digital ecosytem and the digital economy.

IEOR E4507x or y Healthcare operations management
3 pts. Lect: 3.
Prerequisite(s): for senior undergraduate Engineering students: IEOR E3608, E3658, and E4307; for Engineering graduate students (M.S. or Ph.D.): Probability and statistics at the level of IEOR E4150, and deterministic models at the level of IEOR E4004; for healthcare management students: HPMN P8529 Analytical methods for health services management. Develops modeling, analytical, and managerial skills of engineering and health care management students. Enables students to master an array of fundamental operations management tools adapted to the management of health care systems. Through real-world business cases, students learn to identify, model, and analyze operational improvements and innovations in a range of health care contexts.

IEOR E4510y Project management
3 pts. Lect: 3.
Prerequisite(s): IEOR E4004 (or IEOR E3608). Management of complex projects and the tools that are available to assist managers with such projects. Topics include project selection, project teams and organizational issues, project monitoring and control, project risk management, project resource management, and managing multiple projects.

IEOR E4511x or y Industry projects in analytics and operations research
3 pts. Lect: 3.
Teams of students work on real-world projects in analytics. Focus on three aspects of analytics: identifying client analytical requirements; assembling, cleaning and organizing data; identifying and implementing analytical techniques (e.g., statistics and/or machine learning); and delivering results in a client-friendly format. Each project has a defined goal and pre-identified data to analyze in one semester. Client facing class. Class requires 10 hours of time per week and possible client visits on Fridays.

IEOR 4520x Applied systems engineering
3 pts. Lect: 3.
Prerequisite(s): B.S. in engineering or applied sciences; professional experience recommended; calculus, probability and statistics, linear algebra. Introduction to fundamental methods used in systems engineering. Rigorous process that translates customer needs into a structured set of specific requirements; synthesizes a system architecture that satisfies those requirements and allocates them in a physical system, meeting cost, schedule, and performance objectives throughout the product life-cycle. Sophisticated modeling of requirements optimization and dependencies, risk management, probabilistic scenario scheduling, verification matrices, and systems-of-systems constructs are synthesized to define the meta-workflow at the top of every major engineering project.

IEOR 4521y Systems engineering tools and methods
3 pts. Lect: 3.
Prerequisite(s): B.S. in engineering or applied sciences; probability and statistics, optimization, linear algebra, and basic economics. Applications of SE tools and methods in various settings. Encompasses modern complex system development environments, including aerospace and defense, transportation, energy, communications, and modern software-intensive systems.

IEOR E4523x and y Data analytics
3 pts. Lect: 3.
Corequisite(s): IEOR E4522 or E4501. IEOR students only; priority to MSBA students. Survey tools available in Python for getting, cleaning, and analyzing data. Obtain data from files (csv, html, json, xml) and databases (Mysql, PostgreSQL, NoSQL), cover the rudiments of data cleaning, and examine data analysis, machine learning, and data visualization packages (NumPy, pandas, Scikit-lern, bokeh) available in Python. Brief overview of natural language processing, network analysis, and big data tools available in Python. Contains a group project component that will require students to gather, store, and analyze a data set of their choosing.

IEOR E4524y Analytics in practice
3 pts. Lect: 3.
Prerequisite(s): IEOR E4522 or E4501 and IEOR E4523. MSBA students only. Groups of students will work on real world projects in analytics, focusing on three aspects: identifying client analytical requirements; assembling, cleaning, and organizing data; identifying and implementing analytical techniques (statistics, OR, machine learning); and delivering results in a client-friendly format. Each project has a well-defined goal, comes with sources of data pre-identified, and has been structured so that it can be completed in one semester. Client-facing class with numerous on-site client visits; students should keep Fridays clear for this purpose.

IEOR E4525y Machine learning for financial engineering and operations research
3 pts. Lect: 3.
Prerequisite(s): Optimization, applied probability, statistics, and knowledge of (or experience in) computer programming. MS IEOR students only. Introduction to machine learning, practical use of ML algorithms and applications to financial engineering and operations. Supervised learning: regression, classification, resampling methods, regularization, support vector machines (SVMs), and deep learning. Unsupervised learning: dimensionality reduction, matrix decomposition, and clustering algorithms.

IEOR E4526x or y Analytics on the cloud
3 pts. Lect: 3.
Prerequisite(s): IEOR E4501 and E4523. To introduce students to programming issues around working with clouds for data analytics. Class will learn how to work with infrastructure of cloud platforms, and discussion about distributed computing, focus of course is on programming. Topics covered include MapReduce, parallelism, rewriting of algorithms (statistical, OR, and machine learning) for the cloud, and basics of porting applications so that they run on the cloud.

ORCS E4529y Reinforcement learning
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): Probability and statistics, basic optimization (e.g., familiarity with linear and convex optimization, gradient descent, basic algorithm design constructs), familiarity with programming in Python. Markov Decision Processes (MDP) and Reinforcement Learning (RL) problems. Reinforcement Learning algorithms including Q-learning, policy gradient methods, actor-critic method. Reinforcement learning while doing exploration-exploitation dilemma, multi-armed bandit problem. Monte Carlo Tree Search methods; Distributional, Multi-agent, and Causal Reinforcement Learning.

IEOR E4532x and y Data visualization
1.5 pts. Lect: 1.5.
Data visualization and how to build a story with data. Using complex data or statistics to communicate results effectively. Learn to present analysis and results concisely and effectively.

IEOR E4533x and y Performance, objectives, and results using analytics
1.5 pts. Lect: 1.5.
OKR framework and different variations. Measurement techniques (A/B testing, validation, correlation, etc.). Identifying what to measure in product experience and business initiatives. Data-driven decision making.

IEOR E4534x and y Applied analytics: from data to decisions
3 pts. Lect: 3. Professor Lecci.
OKR framework and different variations. Measurement techniques (A/B testing, validation, correlation, etc.). Identifying what to measure in product experience and business initiatives. Data-driven decision making.

IEOR E4540x and y Data mining for engineers
3 pts. Lect: 3.
Prerequisite(s): Linear Algebra, Calculus, Probability, and some basic programming. Course covers major statistical learning methods for data mining under both supervised and unsupervised settings. Topics covered include linear regression and classification, model selection and regularization, tree-based methods, support vector machines, and unsupervised learning. Students learn about principles underlying each method, how to determine which methods are most suited to applied settings, concepts behind model fitting and parameter tuning, and how to apply methods in practice and assess their performance. Emphasizes roles of statistical modeling and optimization in data mining.

IEOR E4544x Statistical methods for analytics
3 pts. Lect: 3.
Focus on advanced statistical techniques for a career in data science or business analytics. Covers the use of writing probabilistic models for data-generating processes, using Bayesian Methods/MCMC to solve such problems. Emphasizes problem identification and general problem-solving tools. Special Topics: Survival Analysis, Missing Data, Robust Statistics, Sequential Analysis, Multiple Testing. Assignments are case-based.

IEOR E4545y Causal analysis for data analytics and OR
3 pts. Lect: 3.
Survey of different approaches to causal inference with an emphasis on applications. Counterfactuals, Causal Structural Models and Graphical Models. G-formula, IP weighting, and g-estimation. Backdoor and Frontdoor adjustment, introduction to the docalculus. Regression discontinuity, Instrumental Variables, Difference-in-Difference, Synthetic Control. Advanced Topics: Causal Survival Analysis, Time-Varying Treatments, Competing Events. Emphasis on problem-solving and working with data.

IEOR E4550x Entrepreneural business creation for engineers
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): IEOR E2261. Required for undergraduate students majoring in OR:EMS. Introduces the basic concepts and methodologies that are used by the nonengineering part of the world in creating, funding, investing in, relating to, and operating entrepreneurial ventures. The first half of the course focuses on the underpinning principles and skills required in recognizing, analyzing, evaluating, and nurturing a business idea. The second half focuses on basic legal knowledge necessary in creating a business entity, defending your business assets, and in promoting effective interaction with other individuals and organizations.

IEOR E4555x or y Design and agile project management engineering lab
3 pts. Lect: 3. Not offered in 2024–2025.
Intensive, team-, and project-based seminar covering multidisciplinary approach to evidence-based product design; agile project planning and execution; rapid MVP prototyping; and launch strategy formulation and implementation. Focuses on practical use of design thinking, design studio, and iterative design sprint methodologies. Systematic approaches to Lean User Research, User Experience (UX), and User Interface (UI) design and deployment are integral components of course curriculum. Mix of startup and enterprise projects, including application drive, data-driven, or combination of both. Teams are fully supported in devising prototypes and actualizing proposed solutions.

IEOR E4561x or y Launch your startup: tech
3 pts. Lect: 3. Not offered in 2024–2025
Tools and knowledge to develop a comprehensive new venture that is scalable, repeatable, and capital efficient. Covers customer discovery, market sizing, pricing, competition, distribution, funding, developing a minimal viable product, and other facets of creating new ventures. A company blueprint and final investor pitch are deliverables.

IEOR E4562x, y, or s Innovate using design thinking
3 pts. Lect: 3.
How Design Thinking can enhance innovation activities, market impact, value creation, and speed. Topics include: conceptual and practical understanding of design thinking, creative solutions, develop robust practices to lead interdisciplinary teams. Course aims to strengthen individuals and collaborative capabilities to identify customer needs, indirect and qualitative research, create concept hypotheses, develop prototype, defined opportunities into actionable innovation possibilities, and recommendations for client organizations.

IEOR E4563x and y Technology breakthroughs
1.5 pts. Lect: 1.5
Technology breakthroughs driven change, disruption, and transformation of the business landscape/society. Course covers overview of deep learning and neural networks; AI and robotics; imaging and vision; photonics; blockchain; smart/digital cities; and the application of these technologies for creating new products and services.

IEOR E4570-4579x and y Topics in operations research
1.5–3 pts. Lect: 1.5–3. Members of the faculty.
Prerequisite(s): IEOR E4150, E4004, and E4106, or instructor's permission. Each offering of this course is devoted to a particular sector of Operations Research and its contemporary research, practice, and approaches. If topics are different, then course can be taken more than once for credit.

ORCS E4575 x and y Policy for privacy technologies
3 pts. Lect: 3. Professor Cummings.
Introduction to privacy technologies, their use in practice, and privacy regulations. Potential topics include anonymization, differential privacy, cryptography, secure multiparty computation, and legislation. Course material will be based in real-world use cases of these tools.

IEOR E4599x MSBA quantitative bootcamp
0 pts. Lect: 3.
Primer on quantitative and mathematical concepts. Required for all incoming MSBA students.

IEOR E4601y Dynamic pricing and revenue management
3 pts. Lect: 3.
Prerequisite(s): STAT GU4001 and IEOR E4004. Focus on capacity allocation, dynamic pricing and revenue management. Perishable and/or limited product and pricing implications. Applications to various industries including service, airlines, hotel, resource rentals, etc.

IEOR E4602y Quantitative risk management
3 pts. Lect: 3.
Prerequisite(s): STAT GU4001 and IEOR E4106. Risk management models and tools; measure risk using statistical and stochastic methods, hedging and diversification. Examples include insurance

risk, financial risk, and operational risk. Topics covered include VaR, estimating rare events, extreme value analysis, time series estimation of extremal events; axioms of risk measures, hedging using financial options, credit risk modeling, and various insurance risk models.

IEOR E4615y Service engineering
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Introductory courses in probability and statistics such as IEOR E3658 and E4307, and introductory courses in stochastic processes such as IEOR E3106 or IEOR E4106. Focus on service systems viewed as stochastic networks, exploiting the theoretical framework of queueing theory. Includes multidisciplinary perspectives involving Statistics, Psychology, and Marketing. Significant emphasis on data analysis, exploiting data from banks, hospitals, and call centers to demonstrate the use of decision support tools. Analytical models, flow models of service networks, Little's law, measuring methods in face-to-face and computerized systems, forecasting methods, stability of service systems, operational quality of service, economies of scale, staffing, complex service networks, skill-based routing.

IEOR E4620x Pricing models for financial engineering
3 pts. Lect: 3.
Prerequisite(s): IEOR E4700. Required for undergraduate students majoring in OR:FE. Characteristics of commodities or credit derivatives. Case study and pricing of structures and products. Topics covered include swaps, credit derivatives, single tranche CDO, hedging, convertible arbitrage, FX, leverage leases, debt markets, and commodities.

IEOR E4630y Asset allocation
3 pts. Lect: 3.
Prerequisite(s): IEOR E4700. Models for pricing and hedging equity, fixed-income, credit-derivative securities, standard tools for hedging and risk management, models and theoretical foundations for pricing equity options (standard European, American equity options, Asian options), standard Black-Scholes model (with multiasset extension), asset allocation, portfolio optimization, investments over longtime horizons, and pricing of fixed-income derivatives (Ho-Lee, Black-Derman-Toy, Heath-Jarrow-Morton interest rate model).

IEOR E4650x and y Business analytics
3 pts. Lect 3. Recit: 1.
Prerequisite(s): STAT GU4001 or IEOR E4150. Prepares students to gather, describe, and analyze data, using advanced statistical tools to support operations, risk management, and response to disruptions. Analysis is done by targeting economic and financial decisions in complex systems that involve multiple partners. Topics include probability, statistics, hypothesis testing, experimentation, and forecasting.

IEOR E4700x and y Introduction to financial engineering
3 pts. Lect: 3.
Prerequisite(s): IEOR E4106 or E3106. Required for undergraduate students majoring in OR:FE. Introduction to investment and financial instruments via portfolio theory and derivative securities, using basic operations research/engineering methodology. Portfolio theory, arbitrage; Markowitz model, market equilibrium, and the capital asset pricing model. General models for asset price fluctuations in discrete and continuous time. Elementary introduction to Brownian motion and geometric Brownian motion. Option theory; Black-Scholes equation and call option formula. Computational methods such as Monte Carlo simulation.

IEOR E4701x Stochastic models for financial engineering
3 pts. Lect: 3.
Prerequisite(s): STAT GU4001. This graduate course is only for M.S. Program in Financial Engineering students, offered during the summer session. Review of elements of probability theory, Poisson processes, exponential distribution, renewal theory, Wald's equation. Introduction to discrete-time Markov chains and applications to queueing theory, inventory models, branching processes.

IEOR E4703y Monte Carlo simulation
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701. This graduate course is only for M.S. Program in Financial Engineering students. Multivariate random number generation, bootstrapping, Monte Carlo simulation, efficiency improvement techniques. Simulation output analysis, Markov-chain Monte Carlo. Applications to financial engineering. Introduction to financial engineering simulation software and exposure to modeling with real financial data. Note: Students who have taken IEOR E4404 Simulation may not register for this course for credit.

IEOR E4706x Foundations of financial engineering
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701, E4702, and linear algebra. This graduate course is only for M.S. Program in Financial Engineering students, offered during the summer session. Discrete-time models of equity, bond, credit, and foreign-exchange markets. Introduction to derivative markets. Pricing and hedging of derivative securities. Complete and incomplete markets. Introduction to portfolio optimization and the capital asset pricing model.

IEOR E4707y Financial engineering: continuous-time asset pricing
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701. This graduate course is only for MS program in FE students. Modeling, analysis, and computation of derivative securities. Applications of stochastic calculus and stochastic differential equations. Numerical techniques: finite-difference, binomial method, and Monte Carlo.

IEOR E4708y Seminar on important papers in financial engineering
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): IEOR E4703, E4706, probability and statistics. Selected topics of special interest to M.S. students in financial engineering. If topics are different then this course can be taken more than once for credit.

IEOR E4709y Statistical analysis and time series
3 pts. Lect: 3.
Prerequisite(s): Probability and IEOR E4702. Corequisite(s): IEOR E4706, E4707. This graduate course is only for M.S. Program in Financial Engineering students. Empirical analysis of asset prices: heavy tails, test of the predictability of stock returns. Financial time series: ARMA, stochastic volatility, and GARCH models. Regression models: linear regression and test of CAPM, nonlinear regression and fitting of term structures.

IEOR E4710x Fixed income and term structure modeling
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): IEOR E4706, E4707, and computer programming. Interest rate models and numerical techniques for pricing and hedging interest rate contracts and fixed income securities.

IEOR E4711x Global capital markets
3 pts. Lect: 3.
Prerequisite(s): Refer to course syllabus. An introduction to capital markets and investments providing an overview of financial markets and tools for asset valuation. Topics covered include the pricing of fixed-income securities (treasury markets, interest rate swaps futures, etc.), discussions on topics in credit, foreign exchange, sovereign ad securitized markets—private equity and hedge funds, etc.

IEOR E4712x Behavioral finance
1.5 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): IEOR E4700. Behavioral finance is the application of behavioral psychology to financial decision making. Focuses on the portfolio aspect of behavioral finance and briefly touches on other aspects. Compared with classical theory of portfolio choice, behavioral portfolio choice features human being's psychological biases. It builds both on behavioral preference structures different from mean variance theory and expected utility theory and on systematic biases against rational beliefs such as Bayesian rule.

IEOR E4714x Risk management, financial system and financial crisis
1.5 pts. Not offered in 2024–2025.
Risk-taking and risk management are at the heart of the financial system, and of the current financial crisis. An introduction to risk management both from an individual financial firm's and from a public policy viewpoint. Overview of the contemporary financial system, focusing on innovations of the past few decades that have changed how financial risk is generated and distributed among market participants, such as the growth of non-bank financial inte–ƒrmediaries, the increased prevalence of leverage and liquidity risk, and the development of structured credit products. Introduction to the basic quantitative tools used in market, credit, and liquidity risk management. The two strands of the course are brought together to help understand how the financial crisis arose and is playing out, examining the mechanics of runs and the behavior of asset prices during crises. Attempt to understand the emergency programs

deployed by central bankers and other policy makers to address crises historically and today.

IEOR E4715x, s Commodity derivatives
1.5 pts. Not offered in 2024–2025.
Commodities markets have been much in the public eye recently as volatility has increased and they changed from markets dominated by physical participants to ones which have a significant investor component. The largest banks either already have profitable commodities franchises or are actively building them, and money managers and funds are increasingly including these assets in their portfolio mix. The end result is a dramatic increase in focus on these markets from all aspects of the financial markets, including the quantitative end.

IEOR E4718x or y Beyond Black-Scholes: the implied volatility smile
3 pts. Lect: 3.
Prerequisite(s): IEOR E4706, knowledge of derivatives valuation models. During the past 15 years the behavior of market options prices have shown systematic deviations from the classic Black-Scholes model. Examines the empirical behavior of implied volatilities, in particular the volatility smile that now characterizes most markets, the mathematics and intuition behind new models that can account for the smile, and their consequences for hedging and valuation.

IEOR E4720–E4729 x and y Topics in quantitative finance
1.5–3 pts. Lect: 2–2.5. Members of the faculty.
Prerequisite(s): IEOR E4700; additional Prerequisite(s) will be announced depending on offering. Selected topics of interest in the area of quantitative finance. Offerings vary each year; some topics include energy derivatives, experimental finance, foreign exchange and related derivative instruments, inflation derivatives, hedge fund management, modeling equity derivatives in Java, mortgage-backed securities, numerical solutions of partial differential equations, quantitative portfolio management, risk management, trade and technology in financial markets.

IEOR E4731x Credit risk modeling and derivatives
3 pts. Lect: 3.
Prerequisite(s): IEOR E4701 and E4707. Introduction to quantitative modeling of credit risk, with a focus on the pricing of credit derivatives. Focus on the pricing of single-name credit derivatives (credit default swaps) and collateralized debt obligations (CDOs). Detail topics include default and credit risk, multiname default barrier models and multiname reduced form models.

IEOR E4732x Computational methods in finance
3 pts. Lect: 3.
Prerequisite(s): IEOR E4700. MS IEOR students only. Application of various computational methods/techniques in quantitative/computational finance. Transform techniques: fast Fourier transform for data de-noising and pricing, finite difference methods for partial differential equations (PDE), partial integro-differential equations (PIDE), Monte-Carlo simulation techniques in finance, and calibration techniques, filtering and parameter estimation techniques. Computational platform will be C++/Java/Python/Matlab/R.

IEOR E4733x or y Algorithmic trading
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): IEOR E4700. Large and amorphous collection of subjects ranging from the study of market microstructure, to the analysis of optimal trading strategies, to the development of computerized, high-frequency trading strategies. Analysis of these subjects, the scientific and practical issues they involve, and the extensive body of academic literature they have spawned. Attempt to understand and uncover the economic and financial mechanisms that drive and ultimately relate them.

IEOR E4734x Foreign exchange and related derivatives instruments
1.5 pts. Lect: 1.5.
Prerequisite(s): IEOR E4700. Foreign exchange market and its related derivative instruments—the latter being forward contracts, futures, options, and exotic options. What is unusual about foreign exchange is that although it can rightfully claim to be the largest of all financial markets, it remains an area where very few have any meaningful experience. Virtually everyone has traded stocks, bonds, and mutual funds. Comparatively few individuals have ever traded foreign exchange. In part that is because foreign exchange is an interbank market. Ironically the foreign exchange markets may be the best place to trade derivatives and to invent new derivatives—given the massive two-way flow of trading that goes through bank dealing rooms virtually 24 hours a day. And most of that is transacted at razor-thin margins, at least comparatively speaking, a fact that makes the foreign exchange market an ideal platform for derivatives. The emphasis is on familiarizing the student with the nature of the foreign exchange market and those factors that make it special among financial markets, enabling the student to gain a deeper understanding of the related market for derivatives on foreign exchange.

IEOR E4735y Structured and hybrid products
3 pts. Lect: 3.
Prerequisite(s): IEOR E4700. Conceptual and practical understanding of structured and hybrid products from the standpoint of relevant risk factors, design goals and characteristics, pricing, hedging, and risk management. Detailed analysis of the underlying cash-flows, embedded derivative instruments, and various structural features of these transactions, both from the investor and issuer perspectives, and analysis of the impact of the prevailing market conditions and parameters on their pricing and risk characteristics. Numerical methods for valuing and managing risk of structured/hybrid products and their embedded derivatives and their application to equity, interest rates, commodities and currencies, inflation, and credit-related products. Conceptual and mathematical principles underlying these techniques, and practical issues that arise in their implementations in the Microsoft Excel/VBA and other programming environments. Special contractual provisions encountered in structured and hybrid transactions, and incorporation of yield curves, volatility smile, and other features of the underlying processes into pricing and implementation framework for these products.

IEOR E4737x AI applications in finance
3 pts. Lect: 3. Professor Hirsa.
Proficiency in Python & Tensor good understanding of calculus knowledge of linear/matrix algebra basic knowledge of statistics. Data, models, visuals; various facets of AI, applications in finance; areas: fund, manager, security selection, asset allocation, risk management within asset management; fraud detection and prevention; climate finance and risk; data-driven real estate finance; cutting-edge techniques: machine learning, deep learning in computational, quantitative finance; concepts: explainability, interpretability, adversarial machine learning, resilience of AI systems; industry utilization.

IEOR E4738x Programming for FE 1: tools for building financial data and risk systems
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Familiarity with object-oriented programming. Object-oriented programming and database development for building financial data and risk systems; Python and Python's scientific libraries; basic database theory, querying and constructing databases; basic risk management and design of risk systems.

IEOR E4739y Programming for FE 2: implementing high-performance financial systems
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): IEOR E4738 and instructor's permission. Developing effective software implementations in C programming language; modeling of portfolio optimization; modeling of price impact trading models; review of synchronization of programs using the file system; review of synchronization of programs using threads; review of synchronization of programs using sockets; implementation of high-performance simulations in finance.

IEOR E4741x Programming for Financial Engineering
3 pts. Lect: 3.
Covers C++ programming language, applications, and features for financial engineering, and quantitative finance applications. Note: restricted to IEOR MS FE students only.

IEOR E4742x and y Deep learning and its applications in FE and OR
3 pts. Lect: 3.
Selected topics of interest in area of quantitative finance. Some topics include energy derivatives, experimental finance, foreign exchange and related derivative instruments, inflation derivatives, hedge fund management, modeling equity derivatives in Java, mortgage-backed securities, numerical solutions of partial differential equations, quantitative portfolio management, risk management, trade and technology in financial markets. Note: open to IEOR students only.

IEOR E4743s Financial correlations—modeling, trading, risk management &AI
3 pts. Lect: 3. Not offered in 2024–2025
Introduction to math finance, knowledge of work-

ing as a "Quant" in investment banking, hedge funds, algo shop, HFT firm, Fed, Exchange, SEC, IMF, back office, mutual fund, as a trader in risk management, product development, model validation, compliance, reporting, academia. Open only to master's students in IEOR department.

IEOR E4744s Modeling & market making in foreign exchange
1.5 pts. Lect: 1.5. Not offered in 2024–2025
Introduction to topics in modeling and market making in foreign exchange, such as spots markets, forward markets, vanilla option markets, exotic derivative markets, and algorithmic index markets. Open only to master's students in IEOR department.

IEOR E4745x Applied financial risk management
3 pts. Lect: 3.
Prerequisite(s): courses in probability and statistics, instruments of the financial markets, and asset pricing models. Introduces risk management principles, practical implementation and applications, standard market, liquidity, and credit risk measurement techniques, and their drawbacks and limitations. Note: restricted to IEOR students only.

IEOR E4798x Financial Engineering practitioners seminar series
0 pts. Lect: 1.5.
Degree requirement for all MSFE first-year students. Topics in Financial Engineering. Past seminar topics include Evolving Financial Intermediation, Measuring and Using Trading Algorithms Effectively, Path-Dependent Volatility, Artificial Intelligence and Data Science in modern financial decision making, Risk-Based Performance Attribution, and Financial Machine Learning. Meets select Monday evenings.

IEOR E4799x MSFE quantitative and computational bootcamp
0 pts. Lect: 3.
Primer on quantitative and mathematical concepts. Required of all incoming MSFE students.

IEOR E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor’s permission. Research training course. Recommended in preparation for laboratory-related research.

IEOR E4900s, x and y Master’s research or project
1–3 pts. Members of the faculty.
Prerequisite(s): Approval by a faculty member who agrees to supervise the work. Independent work involving experiments, computer programming, analytical investigation, or engineering design.

IEOR E4998y Managing technological innovation and entrepreneurship
3 pts. Lect: 3.
A required course for undergraduate students majoring in OR:EMS. Focus on the management and consequences of technology-based innovation. Explores how new industries are created, how existing industries can be transformed by new technologies, the linkages between technological development and the creation of wealth and the management challenges of pursuing strategic innovation.

IEOR E4999s, x and y Fieldwork
1–1.5 pts (up to 2 pts, summer only).
Prerequisite(s): Obtained internship and approval from faculty adviser. Only for IEOR graduate students who need relevant work experience as part of their program of study. Final reports required. May not be taken for pass/fail credit or audited.

MSIE W6408y Inventory theory
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Probability theory, dynamic programming. Construction and analysis of mathematical models used in the design and analysis of inventory systems. Deterministic and stochastic demands and lead times. Optimality of (s, S) policies. Multiproduct and multiechelon systems. Computational methods.

IEOR E6602y Nonlinear and convex programming
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Ph.D.-level linear programming. Convex sets and functions, convex duality and optimality conditions. Computational methods: steepest descent, Newton and quasi-Newton methods for unconstrained problems, active set, penalty set, interior point, augmented Lagrangian and sequential quadratic programming methods for constrained problems. Introduction to nondifferentiable optimization and bundle methods.

IEOR E6613x Optimization, I
4.5 pts. Lect: 3.
Prerequisite(s): Linear algebra. Theory and geometry of linear programming. The simplex method. Duality theory, sensitivity analysis, column generation and decomposition. Interior point methods. Introduction to nonlinear optimization: convexity, optimality conditions, steepest descent, and Newton’s method, active set, and barrier methods.

IEOR E6614y Optimization, II
4.5 pts. Lect: 3.
Prerequisite(s): Linear algebra. An introduction to combinatorial optimization, network flows and discrete algorithms. Shortest path problems, maximum flow problems. Matching problems, bipartite and cardinality nonbipartite. Introduction to discrete algorithms and complexity theory: NP-completeness and approximation algorithms.

IEOR E6617x Machine learning and high-dimensional data analysis in operations research
3 pts. Lect: 3.
Discusses recent advances in fields of machine learning: kernel methods, neural networks (various generative adversarial net architectures), and reinforcement learning (with applications in robotics). Quasi Monte Carlo methods in the context of approximating RBF kernels via orthogonal transforms (instances of the structured technique). Will discuss techniques such as TD(0), TD(λ), LSTDQ, LSPI, DQN.

IEOR E6703y Advanced financial engineering
3 pts. Lect: 2. Not offered in 2024–2025.
Prerequisite(s): Probability theory and advanced stochastic models at the SIEO GR6501 level. Review of basic mathematics, including renewal theory and stochastic calculus. Martingale approach to Black-Scholes formula. Optimal stopping and American options. Pricing of continuous and discrete exotic options. Term structure models and pricing of bond options. Jump diffusion models. Applications, including pricing of real and electricity options and hedging of real options.

IEOR E6711x Stochastic models, I
4.5 pts. Lect: 3.
Prerequisite(s): STAT GU4001 or equivalent. Advanced treatment of stochastic modeling in the context of queueing, reliability, manufacturing, insurance risk, financial engineering and other engineering applications. Review of elements of probability theory; exponential distribution; renewal theory; Wald’s equation; Poisson processes. Introduction to both discrete and continuous-time Markov chains; introduction to Brownian motion.

IEOR E6712y Stochastic models, II
4.5 pts. Lect: 3.
Prerequisite(s): IEOR E6711 or equivalent. Continuation of IEOR E6711, covering further topics in stochastic modeling in the context of queueing, reliability, manufacturing, insurance risk, financial engineering, and other engineering applications. Topics from among generalized semi-Markov processes; processes with a nondiscrete state space; point processes; stochastic comparisons; martingales; introduction to stochastic calculus.

IEOR E8100x and y Advanced topics in IEOR
1–3 pts. Members of the faculty.
Prerequisite(s): Faculty adviser’s permission. Selected topics of current research interest. May be taken more than once for credit.

IEOR E9101s, x and y Research
1–6 pts. Members of the faculty.
Before registering, the student must submit an outline of the proposed work for approval by the supervisor and the chair of the Department. Advanced study in a specialized field under the supervision of a member of the department staff. May be repeated for credit.

MATERIALS SCIENCE AND ENGINEERING PROGRAM

Program in the Department of Applied Physics and Applied Mathematics,
sharing teaching and research with the faculty of the Henry Krumb School of Mines.

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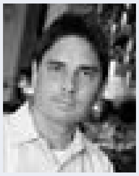
matsci.apam.columbia.edu



PROGRAM CHAIR
Professor William E. Bailey
1140 S. W. Mudd

COMMITTEE ON MATERIALS SCIENCE AND ENGINEERING/SOLID-STATE SCIENCE AND ENGINEERING

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  - Associate Professor of Materials Science
- Katayun Barmak
  - Professor of Materials Science
- Simon J. Billinge
  - Professor of Materials Science
- Siu-Wai Chan
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- Renata Wentzcovitch
  - Professor of Materials Science and Applied Physics, and Earth and Environmental Science
- Yuan Yang
  - Associate Professor of Materials Science
- Nanfang Yu
  - Associate Professor of Applied Physics

Materials Science and Engineering (MSE) focuses on understanding, designing, and producing technology-enabling materials by analyzing the relationships among the synthesis and processing of materials, their properties, and their detailed structure. This includes a wide range of materials such as metals, polymers, ceramics, and semiconductors.

The undergraduate and graduate programs in materials science and engineering are coordinated through the MSE Program in the Department of Applied Physics and Applied Mathematics. This program promotes the interdepartmental nature of the discipline and involves the Departments of Applied Physics and Applied Mathematics, Chemical Engineering and Applied Chemistry, Electrical Engineering, and Earth and Environmental Engineering in the Henry Krumb School of Mines (HKSM) with advisory input from the Departments of Chemistry and Physics.

Students interested in materials science and engineering enroll in the materials science and engineering program in the Department of Applied Physics and Applied Mathematics. Those interested in the solid-state science and engineering specialty enroll in the doctoral program within Applied Physics and Applied Mathematics or Electrical Engineering. The faculty listed above constitute but a small fraction of those participating in materials research.

Materials science and engineering uses optical, electron, and scanning probe microscopy and diffraction techniques to reveal details of structure, ranging from the atomic to the macroscopic scale—details essential to understanding the relationship between materials synthesis and processing and materials properties, including electronic, magnetic, mechanical, optical, and thermal properties. These studies also give insight into problems of the deterioration of materials in service, enabling designers to prolong the useful life of their products. Materials science and engineering also focuses on new ways to synthesize and process materials, from bulk samples to ultrathin films to epitaxial heterostructures to nanocrystals. This involves techniques such as UHV sputtering; molecular beam epitaxy; plasma etching; laser ablation, chemistry, and recrystallization; and other nonequilibrium processes. The widespread use of new materials and the new uses of existing materials in electronics, communications, and computers have intensified the demand for a systematic approach to the problem of relating properties to structure and have necessitated a multidisciplinary approach.

Materials science and solid-state science use techniques such as transport measurements, X-ray photoelectron spectroscopy, ferromagnetic resonance, inelastic light scattering, luminescence, and nonlinear optics to understand electrical, optical, and magnetic properties on a quantum mechanical level. Such methods are used to investigate exciting new types of structures, such as epitaxial metals, two-dimensional transition metal dichalcogenides, superconductors, and semiconductor surfaces and nanocrystals.

Current Research Activities

Current research activities in the materials science and engineering program at Columbia focus on thin films, electronic and magnetic materials, materials at high pressures, materials for advanced batteries, and the structure of materials. Specific topics under investigation include interfaces, stresses, and grain boundaries in thin films; lattice defects and electrical properties of metals and semiconductors; laser processing and ultrarapid solidification of thin films; nucleation in condensed systems; magnetic and electrical properties of semiconductors and metals; synthesis of nanocrystals, two-dimensional materials, and nanotechnology-related materials; deposition, in situ characterization, electronic testing, and ultrafast spectroscopy of magnetoelectronic ultrathin films and heterostructures. In addition, there is research in first-principles electronic structure computation.

LABORATORY FACILITIES

Facilities exist within the Materials Science Laboratory, which also serves as shared facilities for Materials Structural and Mechanical Characterization. Facilities and research opportunities also exist within the 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.

UNDERGRADUATE PROGRAM IN MATERIALS SCIENCE

The objectives of the undergraduate program in the Materials Science Program of the Department of Applied Physics and Applied Mathematics are as follows:

1. Professional employment in industry, including materials production, automotive, aerospace, microelectronics, information storage, medical devices, energy production, storage and conversion, and in engineering consulting firms.
2. Graduate studies in materials science and engineering or related fields.

The undergraduate curriculum is designed to provide the basis for developing, improving, and understanding materials and processes for application in engineered systems. It draws from physics, chemistry and other disciplines to provide a coherent background for immediate application in engineering or for subsequent advanced study. The emphasis is on fundamentals relating atomic-to-microscopic-scale phenomena to materials properties and processing, including design and control of industrially important materials processes. Core courses and electives combine rigor with flexibility and provide opportunities for focusing on such areas as nanomaterials, materials for green energy, materials for infrastructure and manufacturing, materials for health and biotechnology, and materials for next generation electronics.

The unifying theme of understanding and interrelating materials synthesis, processing, structure, and properties forms the basis of our program and is evident in the undergraduate curriculum and in faculty research activities. These activities include work on polycrystalline silicon for flat panel displays; semiconductors for lasers and solar cell applications, magnetic heterostructures for information storage and novel computation architectures; electronic ceramics for batteries, gas sensors and fuel cells; electrodeposition and corrosion of metals; and the analysis and design of high-temperature reactors and first principles calculations. Through involvement with our research groups, students gain valuable hands-on experience and are often engaged in joint projects with industrial and government laboratories.

Students are strongly encouraged to take courses in the order specified in the course tables; implications of deviations should be discussed with a departmental adviser before registration. The first two years provide a strong grounding in the physical and chemical sciences, materials fundamentals, and mathematics. This background is used to provide a unique physical approach to the study of materials. The last two years of the undergraduate program provide substantial exposure to modern materials science and include courses in processing, structure and properties of materials that extend the work of the first two years. Graduates of the program are equipped for employment in industry. Graduates are prepared for graduate study in materials science and engineering and related fields.

Required Materials Science Courses

Students are required to take 13 Materials Science courses for a total of 37 points. The required courses are *MSAE E3010, E3012, E3013, E3100, E3156, E3157, E3201, E4202, E4206, E4215, E4250, and one MSAE 3000-, 4000-, or 6000-level elective.*

Technical Elective Requirements

Students are required to take nine technical electives (27 points) from the list given below, which offers significant flexibility in allowing students to tailor their degree program to their interests.

a. All 3000-level or higher courses in the Materials Science program of the Department of Applied Physics and Applied Mathematics, except those MSAE courses that are required.
b. All 3000-level or higher courses in Applied Physics or Applied Math Programs of the Department of Applied Physics and Applied Mathematics.
c. All 3000-level or higher courses in the Department of Biomedical Engineering, Civil Engineering and Engineering Mechanics program, Department of Chemical Engineering, Department of Computer Science, Department of Earth and Environmental Engineering, Department of Electrical Engineering, Department of Industrial Engineering and Operations Research, and Department of Mechanical Engineering, except for courses that require graduate standing.
d. ORCA E2500 Foundations of data science
e. Courses in the Department of Chemistry listed in the Focus Areas below.

Focus Areas for technical electives are listed below. Students may choose from any one area if they so choose. They are not required to do so.

NANOMATERIALS

APPH E3100y: Intro to quantum mechanics
CHEM GU4071x: Inorganic chemistry
MSAE E4090y: Nanotechnology
APPH E4100x: Quantum physics of matter
CHEM GU4168x: Materials chemistry, I
ELEN E4193x: Modern display technology
MECE E4212x or y: Microelectromechanical systems
BMEN E4550y: Micro- and nanostructures in cellular engineering
ELEN E4944x: Principles of device microfabrication

MATERIALS FOR NEXT GENERATION ELECTRONICS

APPH E3100y: Intro to quantum mechanics
ELEN E3106x: Solid state devices-materials
APPH E4100x: Quantum physics of matter
ELEN E4301y: Intro to semiconductor devices
ELEN E4944x: Principles of device microfabrication

MATERIALS FOR GREEN ENERGY

EAEE E3103x: Energy, minerals, materials systems

MATERIALS SCIENCE PROGRAM: FIRST AND SECOND YEARS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) either semester	
				and APMA E2101 (3)
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	UN1403 (3) UN2601 (3.5)	
CHEMISTRY	UN1403 (4) **or** UN1404 (4) **or** UN2045 (4) **or** UN1604 (4)			
REQUIRED LAB	PHYS UN1493 (3) **or** UN3081 (2) **or** CHEM UN1500 (3) **or** UN1507 (3) **or** UN3085 (4)			
UNIVERSITY WRITING	CC1010 (3) either semester			
NONTECHNICAL REQUIREMENTS[1]	HUMA CC1001, COCI CC1101, **or** Global Core (3–4); HUMA UN1121 (3) **or** UN1123 (3); HUMA CC1002, COCI CC1102, **or** Global Core (3–4); ECON UN1105 (4) **and** UN1155 recitation (0)			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			
COMPUTER SCIENCE	ENGI E1006 (3) any semester			
TECHNICAL REQUIREMENTS			MSAE E3010 (3) Foundations of materials science	

[1] Some nontech courses can be postponed to junior or senior year, so lab courses MSAE E3012 and MSAE E3013 can be taken along with MSAE E3010.

EAEE E4004x: Physical processing and recovery of solids
CHEE E4050x: Industrial and environmental electrochemistry
CHEM GU4071x: Inorganic chemistry
APPH E4130: Physics of solar energy
EAEE E4190x: Photovoltaic systems engineering and sustainability
EAIA E4200y: Alternative energy resources
MECE E4210x: Energy infrastructure planning
MECE E4211y: Energy: sources and conversion
EAEE E4550x: Catalysis for emissions control

MATERIALS FOR 21ST CENTURY INFRASTRUCTURE AND MANUFACTURING

CIEE E3255y: Environmental control and pollution reduction systems
CIEE E3260y: Engineering for community development
ENME E3114y: Experimental mechanics of materials
MECE E3610y: Materials and processes in manufacturing
ENME E4113x: Advanced mechanics of solids
ENME E4114y: Mechanics of fracture and fatigue
ENME E4115y: Micromechanics of composite materials
CIEN E4226y: Advanced design of steel structures
CHEE E4530x: Corrosion of metals

MATERIALS FOR HEALTH AND BIOTECHNOLOGY

CHEM UN2443x-UN2444y: Organic chemistry
APPH E3400y: Physics of the human body
CHEM GU4168x: Materials chemistry, I
BMEN E4210y: Thermodynamics of biological systems
BMEN E4301x: Structure, mechanics, and adaptation of bone
BMEN E4310x or y: Solid biomechanics
BMEN E4450y: Dental and craniofacial tissue engineering
BMEN E4501x: Tissue engineering, I: biomaterials and scaffold design
CHEE E4530y: Corrosion of metals
BMEN E4550x: Micro- and nanostructures in cellular engineering

Note that* **BIOL UN2005x: *Introductory biology, I and* **BIOL UN2006y:** *Introductory biology, II are prerequisites for a number of courses in this track.*

MATERIALS CHEMISTRY/SOFT MATERIALS

CHEM UN2443x-UN2444y: Organic chemistry

MATERIALS SCIENCE: THIRD AND FOURTH YEARS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	MSAE E3012 (3)[1] Laboratory in mat. sci. I MSAE E3100 (3) Crystallography MSAE E4102 (3) Synthesis and processing of materials	MSAE E3013 (3)[1] Laboratory in mat. sci. II MSAE E3201 (3) Materials thermodynamics and phase diagrams MSAE E4250 (3) Ceramics and composites	MSAE E3156 (2) Design project MSAE E4206 (3) Electronic and magnetic properties of solids MSAE Elective (3) 3000-, 4000-, or 6000-level	MSAE E3157 (2) Design project MSAE E4202 (3) Kinetics of transformations in materials MSAE E4215 (3) Mechanical behavior of materials
TECHNICAL ELECTIVES	Students must complete 27 units of Technical Electives.			
NONTECHNICAL ELECTIVES	Students must complete the 27-point requirement.[2]			

[1] Motivated students are highly encouraged to take MSAE E3012 and MSAE E3103 in the sophomore year to obtain practical understanding of material covered in the junior and senior years.

[2] See page 9 for details (administered by the advising dean).

MATERIALS SCIENCE: THIRD AND FOURTH YEARS (TRANSFER STUDENTS)

	SEMESTER 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 E4102 (3) Synthesis and processing of materials	MSAE E3013 (3) Laboratory in materials science, II MSAE E3201 (3) Materials thermodynamics and phase diagrams MSAE E4250 (3) Ceramics and composites	MSAE E3156 (2) Design project MSAE E3100 (3) Crystallography MSAE E4206 (3) Electronic and magnetic properties of solids MSAE Elective (3) 3000-, 4000-, or 6000-level	MSAE E3157 (2) Design project MSAE E4202 (3) Kinetics of transformations in materials MSAE E4215 (3) Mechanical behavior of materials
TECHNICAL ELECTIVES	Students must complete 27 or 24 units of Technical Electives.[1]			
NONTECHNICAL ELECTIVES	Students must complete the 27-point requirement.[2]			

[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 for details (administered by the advising dean). Combined Plan 3/2 transfer students do not need nontechnical electives; see page 14.

CHEN E4201: Applications of electrochemistry
CHEE E4252: Intro surface & colloid chemistry
CHEN E4620: Intro polymers / soft materials
CHEN E4640: Polymer surfaces and interfaces

Nontechnical Elective Requirements

All materials science students are also expected to register for nontechnical electives, both those specifically required by the School of Engineering and Applied Science and those needed to meet the 27-point total of nontechnical electives required for graduation.

Transfer Students

Combined Plan 3-2/Transfer students and students transferring from another SEAS department into the Materials Science Program in the junior year (upon approval of the Materials Science Undergraduate Transfer Committee) will take the following courses to satisfy the degree requirements: *MSAE E3010, E3012, E3013, E3100, E3156, E3157, E3201, E4102, E4202, E4206, E4215, and E4250, and one MSAE 3000-, 4000-, or 6000-level elective.*

Combined Plan 3-2/Transfer Students will be guided by their academic advisers to avoid duplication of courses previously taken. The course tables describe the four-semester program schedule of courses leading to the bachelor's degree in the Materials Science Program of the Department of Applied Physics and Applied Mathematics.

GRADUATE PROGRAMS IN MATERIALS SCIENCE AND ENGINEERING

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

Master of Science Degree

Candidates for the Master of Science degree in Materials Science and Engineering will follow a program of study formulated in consultation with and approved by a faculty adviser. Thirty points of credit (typically ten three-point courses) are required for the degree. The requirements include:

- Eighteen (18) points, MSAE 4000-, 6000-, 8000- level courses (max three points of research)
- Six (6) points, approved electives (see following list) which may not include research points, e.g. MSAE6273
- Six (6) points, general electives (which may include three additional points of research.)

Of the 30 points of credit required for the MS degree, 18 points of MSAE 4000-, 6000-, or 8000-level courses must be included. Only three points of research (MSAE 6273 or other research course) may be used to satisfy the MSAE point requirement. A minimum of six points of MSAE courses must be taken in the first semester. Furthermore, it is expected that 15 of the first 24 points taken will be in MSAE courses; any exceptions must be approved by a faculty adviser.

Six points of restricted electives may be chosen from the following list of approved electives; a course not on the approved list can be counted only with prior, written approval. Research units may not be included.

Six points of electives may be chosen freely. These electives may include MSAE courses, approved electives, other electives, or an additional three points of research. As a reminder, no undergraduate courses (3000-level or below) may be counted toward the degree.

Students who do not have an undergraduate degree in Materials Science and Engineering may be required to take MSAE4301, Materials Science Laboratory, in the first semester. Students will be informed whether they are required to take this course based on a review of their undergraduate transcripts, no later than the first week of classes. The three credits for this course will be counted against the six points of general electives, and not against the six points of restricted electives or eighteen points of MSAE courses.

Students interested in a specific focus in metallurgy or other areas in materials science and engineering should consult their faculty adviser for relevant course listings.

Electives:

MSAE E4000-, 6000- or 8000-level courses, except MSAE E6273
APCH E4080: Soft condensed matter
APMA E4101: Dynamical systems
APMA E4200: Partial differential equations
APMA E4204: Functions of a complex variable
APMA E4300: Computational mathematics: intro to numerical methods
APPH E4100: Quantum physics of matter
APPH E4110: Modern optics
APPH E4112: Laser physics
APPH E4200: Physics of fluids
APPH E4300: Applied electrodynamics
APPH E4990: Special topics in applied physics
APPH E6081: Solid state physics
BMEN E4300: Solid biomechanics
BMEN E4580: Foundations of nanobioscience and nanobiotechnology
CEEM E4113: Advanced mechanics of solids
CEEM E4114: Mechanics of fracture and fatigue
CIEN E4021: Elastic and plastic analysis of structures
CHEN E4201: Engineering applications of electrochemistry
CHEN E4630: Topics in soft materials
CHEN E4880: Atomistic simulations for science and engineering
EAEE E4252: Introduction to surface and colloidal chemistry
ELEN E4193: Modern display science and technology
ELEN E4411: Fundamentals of photonics
ELEN E4944/6945: Principles of device microfabrication
ELEN E6412: Lightwave Devices
ELEN E6331/6333: Semiconductor device physics
IEOR E4150: Introduction to probability and statistics
MECE E4212: Microelectromechanical systems
MECE E4213: BioMEMS: design, fabrication, and analysis
MECE E4214: MEMS production and packaging
MECE E4610: Advanced manufacturing processes
MECE E6137: Nanoscale actuation and sensing
STAT GU4001: Introduction to probability and statistics

All degree requirements must be completed within five years. A candidate is required to maintain at least a 2.5 GPA.

Professional Degree; Metallurgical Engineer

The program is designed for engineers who wish to do advanced work beyond the level of the M.S. degree but who do not desire to emphasize research. Admissions requirements include the undergraduate engineering degree, minimum 3.0 GPA, and GRE.

Candidates must complete at least 30 credits of graduate work beyond the M.S., or 60 points of graduate work beyond the B.S. No thesis is required. All degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

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

Core courses:

- EAEE E4001 Industrial ecology of earth resources
- EAEE E4009 Geographic information systems (GIS) for resource, environmental and infrastructure management
- EAEE E4160 Solid and hazardous waste materials
- EAEE E4900 Applied transport/chemical rate phenomena
- EAEE E6255-6 Methods and applications of analytical decision making in mineral industries

Elective courses must be five courses at the 4000 or higher level from within the Earth and Environmental Engineering Department, the Chemical Engineering Department, Materials Science Program, or others as approved by the adviser. These include but are not limited to: EAEE E4150, CHEE E4252, CIEE E4252, EAEE E4256, EAEE E4257, EAEE E6208. Although it is not required, interested students may choose to complete up to six credits in MSAE E9259-60.

Doctoral Program

At the end of the first year of graduate study in the doctoral program, candidates are required to take a comprehensive written qualifying examination, which is designed to test the ability of the candidate to apply coursework in problem solving and creative thinking. The standard is first-year graduate level. There are two four-hour examinations over a two-day period.

Candidates in the program must take the oral examination by the end of the spring semester of their second year. Candidates must submit a written proposal and defend it orally before a Thesis Proposal Defense Committee consisting of three members of the faculty, including the adviser, in the spring semester of their third year. Doctoral candidates must submit a thesis to be defended before a Dissertation Defense Committee consisting of five faculty members, including two professors from outside the doctoral program. Requirements for the Eng. Sc.D. (administered by the School of Engineering and Applied Science) and the Ph.D. (administered by the Graduate School of Arts and Sciences) can be found on pages 24-25.

Areas of Research

Materials science and engineering is concerned with synthesis, processing, structure, and properties of metals, ceramics, and other materials, with emphasis on understanding and exploiting relationships among structure, properties, and applications requirements. Our graduate research programs encompass research areas as diverse as polycrystalline silicon, electronic ceramics grain boundaries and interfaces, microstructure and stresses in microelectronics thin films, oxide thin films for novel sensors and fuel cells, optical diagnostics of thin-film processing, ceramic nanocomposites, electrodeposition and corrosion processes, structure, properties, and transmission electron microscopy and crystal orientation mapping, magnetic thin films for spintronic applications, chemical synthesis of nanoscale materials, nanocrystals, two-dimensional materials, nanostructure analysis using X-ray and neutron diffraction techniques, and electronic structure calculation of materials using density functional and dynamical mean-field theories. Application targets for polycrystalline silicon are thin film transistors for active matrix displays and silicon-on-insulator structures for ULSI devices. Novel applications are being developed for oxide thin films, including uncooled IR focal plane arrays and integrated fuel cells for portable equipment.

Thin film synthesis and processing in this program include evaporation, sputtering, electrodeposition, and plasma and laser processing. For analyzing materials structures and properties, faculty and students employ electron microscopy, scanning probe microscopy, photoluminescence, magnetotransport measurements, and X-ray diffraction techniques. Faculty members have research collaborations with IBM, and other New York area research and manufacturing centers, as well as major international research centers. Scientists and engineers from these institutions also serve as adjunct faculty members at Columbia. The National Synchrotron Light Source at Brookhaven National Laboratory is used for high-resolution X-ray diffraction and absorption measurements.

Entering students typically have undergraduate degrees in materials science, metallurgy, physics, chemistry, or other science and engineering disciplines. First-year graduate courses provide a common base of knowledge and technical skills for more advanced courses and for research. In addition to coursework, students usually begin an association with a research group, individual laboratory work, and participation in graduate seminars during their first year.

COURSES IN MATERIALS SCIENCE AND ENGINEERING

For related courses, see also Applied Physics and Applied Mathematics, Chemical Engineering, Earth and Environmental Engineering, Electrical Engineering, and Mechanical Engineering.

MSAE E3010x Foundations of materials science
3 pts. Lect: 3. Professor Billinge.
Prerequisite(s): CHEM UN1404 and PHYS UN1011. Introduction to quantum mechanics: atoms, electron shells, bands, bonding; introduction to group theory: crystal structures, symmetry, crystallography; introduction to materials classes: metals, ceramics, polymers, liquid crystals, nanomaterials; introduction to polycrystals and disordered materials; noncrystalline and amorphous structures; grain boundary structures, diffusion; phase transformations; phase diagrams, time-temperature-transformation diagrams; properties of single crystals: optical properties, electrical properties, magnetic properties, thermal properties, mechanical properties, and failure of polycrystalline and amorphous materials.

MSAE E3012y Laboratory in materials science, I
3 pts. Lect: 3. Professor Noyan.
Prerequisite(s): MSAE E3010. Measurement of electrical, thermal, and magnetic properties of single crystals. Single crystal diffraction analysis, polarized light microscopy, and infrared microscopy in Si single crystals, written and oral reports.

MSAE E3013y Laboratory in materials science, II

3 pts. Lect: 3. Professor Noyan.
Prerequisite(s): MSAE E3012. Metallographic sample preparation, optical microscopy, quantitative metallography, hardness and tensile testing, plastic deformation, annealing, phase diagrams, brittle fracture of glass, temperature and strain-rate dependent deformation of polymers; written and oral reports. This is the second of a two-semester sequence materials laboratory course.

MSAE E3100x Crystallography
3 pts. Lect: 3. Professor Barmak.
Prerequisite(s): CHEM UN1403, PHYS UN1403, APMA E2101, or equivalent. A first course in crystallography, crystal symmetry, Bravais lattices, point groups and space groups. Diffraction and diffracted intensities. Exposition of typical crystal structures in engineering materials, including metals, ceramics and semiconductors. Crystalline anisotropy. Note: MSAE E4100 shares lectures and meeting times with E3100. Undergraduates may not take both E3100 and E4100 for credit.

MSAE E3111x Thermodynamics, kinetic theory and statistical mechanics
3 pts. Lect: 3. Professor Bailey.
An introduction to the basic thermodynamics of systems, including concepts of equilibrium, entropy, thermodynamic functions, and phase changes. Basic kinetic theory and statistical mechanics, including diffusion processes, concept of phase space, classical and quantum statistics, and applications thereof.

MSAE E3141y Processing of metals and semiconductors
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E3011 or equivalent. Synthesis and production of metals and semiconductors with engineered microstructures for desired properties. Includes high-temperature, aqueous, and electrochemical processing; thermal and mechanical processing of metals and alloys; casting and solidification; diffusion, microstructural evolution, and phase transformations; modification and processing of surfaces and interfaces; deposition and removal of thin films. Processing of Si and other materials for elemental and compound semiconductor-based electronic, magnetic, and optical devices.

MSAE E3142y Processing of ceramics and polymers
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E3011 or equivalent. Established and novel methods involved in the processing of polymers and ceramics. The fundamental aspects of the structure and properties of polymers and ceramic materials; strategy in the preparatory, synthesis, and processing methods for obtaining them. Topics include polymer synthesis, elastomers, thermoplastics, thermoset materials, design and molding processes. Ceramics: inorganic glasses and composites, materials production and principle inorganic chemistry. Processing methodology, conditioning, drying, forming, sintering, and microstructure development. Relevant aspects of transport phenomena, colloid and sol-gel science, contemporary issues in modern polymer and ceramic processing.

MSAE E3156x-E3157y Design project
2 pts (each semester). Lect.: 3.
Professor Billinge.
Prerequisite(s): Senior standing. Written permission from instructor and approval from adviser. E3156: A design problem in materials science or metallurgical engineering selected jointly by the student and a professor in the department. The project requires research by the student, directed reading, and regular conferences with the professor in charge. E3157: Completion of the research, directed reading, and conferences, culminating in a written report and an oral presentation to the department.

MSAE E3201y Materials thermodynamics and phase diagrams
3 pts. Lect: 3. Professor Wentzcovitch.
Prerequisite(s): MSAE E3010, or equivalent or instructor's permission. Review of laws of thermodynamics, thermodynamic variables and relations, free energies and equilibrium in thermodynamic systems. Unary, binary, and ternary phase diagrams, compounds and intermediate phases, solid solutions and Hume-Rothery rules, relationship between phase diagrams and metastability, defects in crystals. Thermodynamics of surfaces and interfaces, effect of particle size on phase equilibria, adsorption isotherms, grain boundaries, surface energy, electrochemistry, statistical mechanics. Note: MSAE E4100 shares lectures and meeting times with E3100. Undergraduates may not take both E3100 and E4100 for credit.

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

MSAE E4090y Nanotechnology
3 pts. Lect: 3. Professor Yang.
Prerequisite(s): APPH E3100 and MSAE E3010 or their equivalents with instructor's permission. The science and engineering of creating materials, functional structures and devices on the nanometer scale. Carbon nanotubes, nanocrystals, quantum dots, size dependent properties, self-assembly, nanostructured materials. Devices and applications, nanofabrication. Molecular engineering, bionanotechnology. Imaging and manipulating at the atomic scale. Nanotechnology in society and industry. Offered in alternate years.

MSAE E4100x Crystallography
3 pts. Lect: 3. Professor Barmak.
Prerequisite(s): CHEM UN1403, PHYS UN1403, APMA E2101, or equivalent. A first course on crystallography. Crystal symmetry, Bravais lattices, point groups, space groups. Diffraction and diffracted intensities. Exposition of typical crystal structures in engineering materials, including metals, ceramics, and semiconductors. Crystalline anisotropy. Note: MSAE E4100 shares lectures and meeting times with E3100. Undergraduates may not take both E3100 and E4100 for credit.

MSAE E4102y Synthesis and processing of materials
3 pts. Lect: 3. Professor Im.
Prerequisite(s): MSAE E3010 or equivalent or instructor's permission. A course on synthesis and processing of engineering materials. Established and novel methods to produce all types of materials (including metals, semiconductors, ceramics, polymers, and composites). Fundamental and applied topics relevant to optimizing the microstructure of the materials with desired properties. Synthesis and processing of bulk, thin-film, and nano materials for various mechanical and electronic applications.

MSAE E4105y Ceramic nanomaterials
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): CHEM UN1404 or equivalent undergraduate thermodynamics. Ceramic nanomaterials and nanostructures: synthesis, characterization, size-dependent properties, and applications; surface energy, surface tension and surface stress; effect of ligands, surfactants, adsorbents, isoelectric point, and surface charges; supersaturation and homogenous nucleation for monodispersity.

MSAE E4132y Fundamentals of polymers and ceramics
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E3010 or instructor's permission. The science and engineering of polymer, ceramic and composite inorganic materials. Fundamental aspects of structure, processing and properties. Polymers: classification, synthesis, elastomers, thermoplastics, thermosets; ceramics: Crystal structure, morphology, classification, oxides, nitrides, carbides, silicates. Electrical, mechanical, thermal and optical properties. Common and advanced technological applications, electrical/optical devices, catalytic and environmental applications.

MSAE E4200x Theory of crystalline materials: phonons
3 pts. Lect: 3. Professor Marianetti.
Pre/Corequisite: MSAE E4100 or instructor's permission. Phenomenological theoretical understanding of vibrational behavior of crystalline materials; introducing all key concepts at classical level before quantizing the Hamiltonian. Basic notions of Group Theory introduced and exploited: irreducible representations, Great Orthogonality Theorem, character tables, degeneration, product groups, selection rules, etc. Both translational and point symmetry employed to block diagonalize the Hamiltonian and compute observables related to vibrations/phonons. Topics include band structures, density of states, band gap formation, nonlinear (anharmonic) phenomena, elasticity, thermal conductivity, heat capacity, optical properties, ferroelectricity. Illustrated using both minimal model Hamiltonians in addition to accurate Hamiltonians for real materials (e.g., Graphene).

MSAE E4201y Materials thermodynamics and

phase diagrams
3 pts. Lect: 3. Professor Wentzcovitch.
Prerequisite(s): MSAE E3010 or equivalent or instructor’s permission. Review of laws of thermodynamics, thermodynamic variables and relations, free energies and equilibrium in thermodynamic systems, statistical thermodynamics. Unary, binary, and ternary phase diagrams, compounds and of surfaces and interfaces, effect of particle size, intermediate phases, solid solutions and Hume-Rothery rules, relationship between phase diagrams and metastability, defects in crystals. Thermodynamics of surfaces and interfaces, effect of particle size on phase equilibria, adsorption isotherms, grain boundaries, surface energy, electrochemistry. Note: MSAE E4201 shares lectures and meeting times with E3201. Undergraduates may not take both E3201 and E4201 for credit.

MSAE E4202y Kinetics of transformation in materials
3 pts. Lect: 3. Professor Im.
Pre/Corequisite: MSAE E4201. Review of thermodynamics, irreversible thermodynamics, diffusion in crystals and noncrystalline materials, phase transformations via nucleation and growth, overall transformation analysis and time-temperature-transformation (TTT) diagrams, precipitation, grain growth, solidification, spinodal and order-disorder transformations, martensitic transformation.

MSAE E4203y Theory of crystalline materials: electrons
3 pts. Lect: 3. Professor Marianetti.
Prerequisite(s): MSAE E4200 or instructor's permission. Phenomenological theoretical understanding of electrons in crystalline materials. Both translational and point symmetry employed to block diagonalize the Schrödinger equation and compute observables related to electrons. Topics include nearly free electrons, tight-binding, electron-electron interactions, transport, magnetism, optical properties, topological insulators, spin-orbit coupling, and superconductivity. Illustrated using both minimal model Hamiltonians in addition to accurate Hamiltonians for real materials.

MSAE E4206y Electronic and magnetic properties of solids
3 pts. Lect: 3. Professor Bailey.
Prerequisite(s): PHYS UN1401-3 or equivalent. A survey course on the electronic and magnetic properties of materials, oriented toward materials for solid-state devices. Dielectric and magnetic properties, ferroelectrics and ferromagnets. Conductivity and superconductivity. Electronic band theory of solids: classification of metals, insulators, and semiconductors. Materials in devices: examples from semiconductor lasers, cellular telephones, integrated circuits, and magnetic storage devices. Topics from physics are introduced as necessary.

MSAE E4215x Mechanical behavior of structural materials
3 pts. Lect: 3. Professor Noyan.
Prerequisite(s): MSAE E3010. Recommended preparation: A course in mechanics of materials. Review of states of stress and strain and their relations in elastic, plastic, and viscous materials. Dislocation and elastic-plastic concepts introduced to explain work hardening, various materials-strengthening mechanisms, ductility, materials devices, material reliability and fracture, and toughness. Macroscopic and microstructural aspects of brittle and ductile fracture mechanics, creep and fatigue phenomena. Case studies used throughout, including flow and fracture of structural alloys, polymers, hybrid materials, composite materials, ceramics, and electronic prevention emphasized.

MSAE E4250x Ceramics and composites
3 pts. Lect: 3. Professor Chan.
Pre/Corequisites: MSAE E3010 and E3013, or instructor’s permission. Will cover some of the fundamental processes of atomic diffusion, sintering and microstructural evolution, defect chemistry, ionic transport, and electrical properties of ceramic materials. Following this, we will examine applications of ceramic materials, specifically, ceramic thick and thin film materials in the areas of sensors and energy conversion/storage devices such as fuel cells, and batteries. The coursework level assumes that the student has already taken basic courses in the thermodynamics of materials, diffusion in materials, and crystal structures of materials.

MSAE E4260x Electrochemical materials and devices: from structure to performance
3 pts. Lect: 3. Professor Yang.
Prerequisite(s): CHEM UN1403, MSAE E3010, equivalents, or instructor's permission. Overview of electrochemical processes and applications from perspectives of materials and devices. Thermodynamics and principles of electrochemistry, methods to characterize electrochemical processes, application of electrochemical materials and devices, including batteries, supercapacitors, fuel cells, electrochemical sensor, focus on link between material structure, composition, and properties with electrochemical performance.

MSAE E4301x Materials science laboratory
3 pts. Professor Noyan.
Prerequisite(s): Introductory materials course or equivalent and instructor’s permission. General experimental techniques in materials science, including X-ray diffraction, scanning electron microscopies, atomic force microscopy, materials synthesis and thermodynamics, characterization of material properties (mechanical, electrochemical, magnetic, electronic). Additional experiments at discretion of instructor.

MSAE E4990x and y Special topics in materials science and engineering
1–3 pts. Not offered in 2024–2025.
Prerequisite(s): Instructor’s permission. May be repeated for credit. Topics and instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

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

MSAE E6085y Computing the electronic structure of complex materials
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APPH E3100 or equivalent. Basics of density functional theory (DFT) and its application to complex materials. Computation of electronics and mechanical properties of materials. Group theory, numerical methods, basis sets, computing, and running open source DFT codes. Problem sets and a small project.

MSAE E6091y Magnetism and magnetic materials
3 pts. Lect. 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E4206, APPH E6081, or equivalent. Types of magnetism. Band theory of ferromagnetism. Magnetic metals, insulators, and semiconductors. Magnetic nanostructures: ultrathin films, superlattices, and particles. Surface magnetism and spectroscopies. High speed magnetization dynamics. Spin electronics.

MSAE E6100x Transmission electron microscopy
3 pts. Lect: 3. Professor Barmak.
Prerequisite(s): permission of the instructor. Theory and practice of transmission electron microscopy (TEM): principles of electron scattering, diffraction, and microscopy; analytical techniques used to determine local chemistry; introduction to sample preparation; laboratory and in-class remote access demonstrations, several hours of hands-on laboratory operation of the microscope; the use of simulation and analysis software; guest lectures on cryomicroscopy for life sciences and high resolution transmission electron microscopy for physical sciences; and, time permitting, a visit to the electron microscopy facility in the Center for Functional Nanomaterials (CFN) at the Brookhaven National Laboratory (BNL).

MSAE E6229y Energy and particle beam processing of materials
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E4202 or instructor’s permission. Laser-, electron-, and ion-beam modification of materials to achieve unique microstructures and metastable phases for electronic and structural applications. Fundamentals of energy deposition and heat flow during laser- and electron-beam irradiation. Atomic displacement processes in ion-irradiated materials. Beam-induced microstructural evolution, crystallization, surface alloying, rapid solidification, and metastable phase formation. Review of current industrial applications.

MSAE E6230y Kinetics of phase transformations
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MSAE E4202 or instructor’s permission. Principles of nonequilibrium thermodynamics; stochastic equations; nucleation, growth, and coarsening reactions in solids; spinodal decomposition; eutectic and eutectoid

transformations.

MSAE E6251y Thin films and layers
3 pts. Lect: 3. Not offered in 2024–2025.
Vacuum basics, deposition methods, nucleation and growth, epitaxy, critical thickness, defects properties, effect of deposition procedure, mechanical properties, adhesion, interconnects, and electromigration.

MSAE E6273x and y–S6273 Materials science reports
0 to 6 pts. Members of the faculty.
Prerequisite(s): Written permission from instructor and approval from adviser. Formal written reports and conferences with the appropriate member of the faculty on a subject of special interest to the student but not covered in the other course offerings.

MSAE E8235x and y Selected topics in materials science
3 pts. Lect: 3. Not offered in 2024–2025.
May be repeated for credit. Selected topics in materials science. Topics and instructors change from year to year. For students in engineering, physical sciences, biological sciences, and related fields.

MSAE E9259x-E9260y Research topics in materials science and metallurgical engineering
1 pt. Lect: 1. Members of the faculty.
Discussion of a group of technical papers related to a topic of current research interest.

MSAE E9301x-S9301 Doctoral research
0–15 pts. Members of the faculty.
Prerequisite(s): Qualifying examination for doctorate. Required of doctoral candidates.

MSAE E9309x and y–S9309 Proposal of research for the doctorate
0–3 pts. Members of the faculty.
A written report prepared by the prospective doctoral candidate defining the proposed research for the dissertation, and oral defense of the proposal.

MSAE E9800x and y–S9800 Doctoral research instruction
3, 6, 9, or 12 pts. Members of the faculty.
A candidate for the Eng.Sc.D. degree must register for 12 points of doctoral research instruction. Registration in MSAE E9800 may not be used to satisfy the minimum residence requirement for the degree.

MSAE E9900x and y–S9900 Doctoral dissertation
0 pts. Members of the faculty.
A candidate for the doctorate may be required to register for this course every term after the coursework has been completed and until the dissertation has been accepted.

MECHANICAL ENGINEERING

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Enrico Zordan

MANAGER OF INSTRUCTIONAL LABORATORIES
Robert G. Stark

Mechanical engineering is a diverse subject that derives its breadth from the need to design and manufacture everything from small individual parts/devices (e.g., micro-scale sensors, inkjet printer nozzles) to large systems (e.g., spacecraft and machine tools). The role of a mechanical engineer is to take a product from an idea to the marketplace. In order to accomplish this, a broad range of skills are needed. The particular skills in which the mechanical engineer acquires deeper knowledge are the ability to understand the forces and the thermal environment that a product, its parts, or its subsystems will encounter; design them for functionality, aesthetics, and the ability to withstand the forces and the thermal environment they will be subjected to; determine the best way to manufacture them and ensure they will operate without failure. Perhaps the one skill that is the mechanical engineer's exclusive domain is the ability to analyze and design objects and systems with motion.

Since these skills are required for virtually everything that is made, mechanical engineering is perhaps the broadest and most diverse of engineering disciplines. Hence mechanical engineers play a central role in such industries as automotive (from the car chassis to its every subsystem—engine, transmission, sensors); aerospace (airplanes, aircraft engines, control systems for airplanes and spacecraft); biotechnology (implants, prosthetic devices, fluidic systems for pharmaceutical industries); computers and electronics (disk drives, printers, cooling systems, semiconductor tools); microelectromechanical systems, or MEMS (sensors, actuators, micro power generation); energy conversion (gas turbines, wind turbines, solar energy, fuel cells); environmental control (HVAC, air-conditioning, refrigeration, compressors); automation (robots, data/image acquisition, recognition, and control); manufacturing (machining, machine tools, prototyping, microfabrication).

To put it simply, mechanical engineering deals with anything that moves. Mechanical engineers learn about materials, solid and fluid mechanics, thermodynamics, heat transfer, control, instrumentation, design, and manufacturing to realize/understand mechanical systems. Specialized mechanical engineering subjects include biomechanics, cartilage tissue engineering, energy conversion, laser-assisted materials processing, combustion, MEMS, microfluidic devices, fracture mechanics, nanomechanics, mechanisms, micropower generation, tribology (friction and wear), and vibrations. The American Society of Mechanical Engineers (ASME) currently lists thirty-six technical divisions, from advanced energy systems and aerospace engineering to safety engineering and tribology.

The breadth of the mechanical engineering discipline allows students a variety of career options beyond some of the industries listed above. Regardless of the particular future path they envision for themselves after they graduate, their education would have provided them with the creative thinking that allows them to design an exciting product or system, the analytical tools to achieve their design goals, the ability to meet several sometimes conflicting constraints, and the teamwork needed to design, market, and produce a system. These skills also prove to be valuable in other endeavors and can launch a career in medicine, law, consulting, management, banking, finance, and so on.

For those interested in applied scientific and mathematical aspects of the discipline, graduate study in mechanical engineering can lead to a career of research and teaching.

Current Research Activities

Current research activities in the Department of Mechanical Engineering are in the areas of controls and robotics, energy and micropower generation, fluid mechanics, heat/mass transfer, mechanics of materials, manufacturing, material processing, MEMS, nanotechnology, and biomechanics and biofluids.

Biomechanics, Biofluids, and Mechanics of Materials. Some of the current research in biomechanics is concerned with the application of continuum theories of mixtures to problems of electromechanical behavior of soft biological tissues, contact mechanics, lubrication of diarthrodial joints, and cartilage tissue engineering. (Ateshian)

The Kysar group studies the mechanics and mechanical properties of small-scale structures and materials. Examples of material systems include two-dimensional materials such as graphene, nanoporous metal thin films, metallic and polymeric composites containing nanoscale strengthening agents, single crystal metals, and the ear's round Window Membrane, among several others. The work is experimental, theoretical, and computational in nature. The ultimate goal is to understand and predict the mechanical behavior based on fundamental physics and chemistry through the development of multiple length scale models.

At the Kasza Living Materials Lab we are interested in how cells self-organize to build tissues and organs with mechanical properties that are required for proper function. A major focus is to uncover fundamental mechanical and biological mechanisms that coordinate the behaviors of cells in developing tissues. To do this, we study morphogenesis in developing embryos of model organisms and combine approaches such as *in vivo* imaging, optogenetics, and biomechanical measurements. We are leveraging this knowledge to design and build novel cell-based tissue structures and systems. Our goals are to shed light on human health and disease and learn how to better build functional tissues in the lab.

Other areas of biomechanics include characterizing the structure-function behavior of the cervix during the remodeling events of pregnancy and characterizing the mechanical properties of the eye-wall in relation to glaucoma. Research in our lab includes the mechanical testing of biological soft tissues, the biochemical analysis of tissue microstructure, and material modeling based on structure-mechanical property relationships. In collaboration with clinicians, our goal is to understand the etiologies of tissue pathology and disease. (Myers)

A surgically implantable pediatric valve device that can 'grow with the child' would revolutionize current treatment for neonates born with valve disease. In close collaboration with Dr. David Kalfa, who is a pediatric heart surgeon at Columbia University Medical Center, and Dr. Haim Waisman from the Civil Engineering department, the Kysar and Vedula groups are involved in a multidisciplinary NIH-funded project to develop an expendable biostable polymeric valved conduit. The device would be implanted surgically to reconstruct the right ventricular outflow tract in neonates and then expanded by successive transcatheter procedures to reach the adult size. This project involves material design and characterization of the growth potential of a viscoplastic polymer, numerically model the fluid-structure interaction of the valved conduit, optimization for valve competence at every stage of expansion, and assess the biocompatibility and durability in animal models. (Kysar, Vedula)

Control, Robotics, Design, and Manufacturing. Control research emphasizes iterative learning control (ILC) and repetitive control (RC). ILC creates controllers that learn from previous experience performing a specific command, such as robots on an assembly line, aiming for high-precision mechanical motions. RC learns to cancel repetitive disturbances, such as precision motion through gearing, machining, satellite precision pointing, particle accelerators, etc. Time optimal control of robots is being studied for increased productivity on assembly lines through dynamic motion planning. Research is also being conducted on improved system identification, making mathematical models from input-output data. The results can be the starting point for designing controllers, but they are also studied as a means of assessing damage in civil engineering structures from earthquake data. (Longman)

Robotics research focuses on design of novel rehabilitation machines and training algorithms for functional rehabilitation of neural impaired adults and children. The research also aims to design intelligent machines using nonlinear system theoretic principles, computational algorithms for planning, and optimization.

Robotic Systems Engineering (ROSE) Lab develops technology capable of solving difficult design problems, such as cable-actuated systems, under-actuated systems, and others. Robotics and Rehabilitation (ROAR) Lab focuses on developing new and innovative technologies to improve the quality of care and patient outcomes. The lab designs novel exoskeletons for upper and lower limbs training of stroke patients, and mobile platforms to improve socialization in physically impaired infants (Agrawal).

The Robotic Manipulation and Mobility (ROAM) Lab focuses on versatile manipulation and mobility in robotics, aiming for robotic applications pervasive in everyday life. Research areas include manipulation and grasping, interactive or Human-in-the-Loop robotics, dynamic simulators and virtual environments, machine perception and modeling, and many more. We are interested in application domains such as versatile automation in manufacturing and logistics, assistive and rehabilitation robotics in healthcare, space robotics, and mobile manipulation in unstructured environments. (Ciocarlie)

At the Creative Machines Lab (CreativeMachines.org) we are interested in robots that create and robots that are themselves creative. We develop novel autonomous systems that can design and make other machines—automatically. We are working on a self-replicating robots, self-aware robots, robots that improve themselves over time, and robots that compete and cooperate with other robots. We build robots that paint art, cook food, build bridges and fabricate other robots. Our work is inspired from biology, as we seek new biological concepts for engineering and new engineering insights into biology. (Lipson)

In the area of advanced manufacturing processes and systems, current research concentrates on laser materials processing. Investigations are being carried out in laser micromachining; laser forming of sheet metal; microscale laser shock-peening, material processing using improved laser-beam quality. Both numerical and experimental work is conducted using state-of-the-art equipment, instruments, and computing facilities. Close ties with industry have been established for collaborative efforts. (Yao)

Energy, Fluid Mechanics, and Heat/ Mass Transfer. In the area of energy, one effort is in energy systems with an eye toward cost-effective decarbonization using technologies that are at hand or near-ready. The interaction of the electric grid, with buildings, transportation, gas networks, storage and electrofuels is being studied. Another effort addresses the integration of thermal storage into HVAC systems for efficient use of variable renewable energy. The development of measurement, monitoring and control systems using IoT devices for use in micrositing and operation of microgrids and enabling flexibility or demand response of load. (Modi)

In the area of energy, demand estimation and prediction of interest using utility data, satellite imagery and lean, robust field data capture. (Modi)

In the area of nanoscale thermal transport, our research efforts center on the enhancement of thermal radiation transport across interfaces separated by a nanoscale gap. The scaling behavior of nanoscale radiation transport is measured using a novel heat transfer measurement technique based on the deflection of a bimaterial atomic force microscope cantilever. Numerical simulations are also performed to confirm these measurements. The measurements are also used to infer extremely small variations of van der Waals forces with temperature. This enhancement of radiative transfer will ultimately be used to improve the power density of thermophotovoltaic energy conversion devices. (Narayanaswamy)

Also in the area of energy, research is being performed to improve the thermochemical models used in accelerating development of cleaner, more fuel-efficient engines through computational design. In particular, data-driven approaches to creating high-accuracy, uncertainty-quantified thermochemicals models are being developed that utilize both theoretical and experimental data. Special emphasis is placed on the generation and analysis of data across the full range of relevant scales—from the small-scale electronic behavior that governs molecular reactivity to the large-scale turbulent, reactive phenomena that govern engine performance. (Burke)

The Vedula group aims to advance clinical management of cardiovascular disease using computational modeling. We are developing novel computational techniques for performing patient-specific modeling of the cardiovascular system aimed at understanding the role of biomechanical factors in disease and development, device design, and 'virtual' surgery planning. Computational modeling combined with machine learning and data-mining strategies provides unprecedented opportunities to not only examine acute response to treatment, but also predict and risk stratify patients susceptible to long-term remodeling and dysfunction. (Vedula)

The Vedula group is involved in developing multiscale-multiphysics models of the heart coupling cardiac electrophysiology, tissue mechanics, blood flow and valvular interactions, thereby creating an integrated heart model, that could be used to study a variety of cardiac and valvular pediatric and adult cardiovascular disease. A few applications that we are particularly interested in include cardiomyopathies, valvular calcifications and device design, remodeling and dysfunction in congenital heart disease. (Vedula)

In the area of energy, the Building Physics and Energy Systems Laboratory aims to develop new modeling techniques to understand the dynamics of energy demand necessary to facilitate decarbonization in buildings. Research focuses on developing new modeling and simulation methods to provide more accurate estimates of time-vary demand, model-based control system to enable demand flexibility, and hybrid physics and statistical modeling approaches to provide accurate estimates of the timing of demand at the urban scale. (Howard)

MEMS and Nanotechnology. In these areas, research activities focus on power generation systems, nanostructures for photonics, fuel cells and photovoltaics, and microfabricated adaptive cooling skin and sensors for flow, shear, and wind speed. Basic research in fluid dynamics and heat/mass transfer phenomena at small scales also support these activities. (Hone, Kysar, Lin, Modi, Narayanaswamy)

We study the dynamics of microcantilevers and atomic force microscope cantilevers to use them as microscale thermal sensors based on the resonance frequency shifts of vibration modes of the cantilever. Bimaterial microcantilever-based sensors are used to determine the thermophysical properties of thin films. (Narayanaswamy)

Research in the area of nanotechnology focuses on nanomaterials such as nanotubes and nanowires and their applications, especially in nanoelectromechanical systems (NEMS). A laboratory is available for the synthesis of graphene and other two-dimensional materials using chemical vapor deposition (CVD) techniques and to build devices using electron-beam lithography and various etching techniques. This effort will seek to optimize the fabrication, readout, and sensitivity of these devices for numerous applications, such as sensitive detection of mass, charge, and magnetic resonance. (Hone, Kysar, Modi)

Research in BioMEMS aims to design and create MEMS and micro/nanofluidic systems to control the motion and measure the dynamic behavior of biomolecules in solution. Current efforts involve modeling and understanding the physics of micro/ nanofluidic devices and systems, exploiting polymer structures to enable micro/nanofluidic manipulation, and integrating MEMS sensors with microfluidics for measuring physical properties of biomolecules. (Lin)

The Schuck group aims to characterize, understand, and control nanoscale light-matter interactions, with a primary focus on sensing, engineering, and exploiting novel optoelectronic phenomena emerging from nanostructures and interfaces. This offers unprecedented opportunities for developing innovative devices that rely on the dynamic manipulation of single photons and charge carriers. We are continuously developing new multimodal and multidimensional spectroscopic methods that provide unique access to optical, electrical, and structural properties at relevant length scales in real environments encountered in energy and biological applications. (Schuck)

Biological Engineering and Biotechnology. Active areas of research in the musculoskeletal biomechanics laboratory include theoretical and experimental analysis of articular cartilage mechanics; theoretical and experimental analysis of cartilage lubrication, cartilage tissue engineering, and bioreactor design; growth and remodeling of biological tissues; cell mechanics; and mixture theory for biological tissues with experiments and computational analysis (Ateshian).

The Hone laboratory studies two-dimensional (2D) materials such as graphene, with efforts spanning synthesis of single crystals and thin films; device nanofabrication; and testing of electronic, optical, mechanical, and other properties. The group develops methods to combine 2D materials into layered heterostructures, which are used to explore fundamental properties, achieve new functionality, and enable applications in electronics, photonics, sensing, and other areas. (Hone)

The Hone group uses nanofabrication techniques to create tools for studying the role of mechanical forces and geometry in cellular biology. These investigations seek to understand how cells sense the mechanical properties or physical shape of their surroundings, a process that plays a major role in maintaining healthy cellular and tissue function. (Hone)

Microelectromechanical systems (MEMS) are being exploited to enable and facilitate the characterization and manipulation of biomolecules. MEMS technology allows biomolecules to be studied in well-controlled micro/nanoenvironments of miniaturized, integrated devices, and may enable novel biomedical investigations not attainable by conventional techniques. The research interests center on the development of MEMS devices and systems for label-free manipulation and interrogation of biomolecules. Current research efforts primarily involve microfluidic devices that exploit specific and reversible, stimulus-dependent binding between biomolecules and receptor molecules to enable selective purification, concentration, and label-free detection of nucleic acid, protein, and small molecule analytes; miniaturized instruments for label-free characterization of thermodynamic and other physical properties of biomolecules; and subcutaneously implantable MEMS affinity biosensors for continuous monitoring of glucose and other metabolites. (Kysar, Lin)

The Kysar group has a project to design and develop a method to deliver therapeutics into the inner ear through the Round Window Membrane (RWM) that serves as a portal for acoustic energy between the middle ear and inner ear. This involves the design and fabrication of arrays of microneedles, the measurements of diffusive flux of chemical species across a perforated RWM, and the design, delivery, and testing of surgical tools, all in close collaboration with Anil K. Lalwani, M.D., at Columbia University Medical Center. (Kysar)

The Schuck group is involved in engineering novel near-infrared (NIR) upconverting nanoparticles (UCNPs) and UCNP-based microdevices for large-scale sensing applications, including deployment in projects aimed at deep-tissue imaging and the control of neural function deep within brain tissue. UCNPs have the potential to overcome nearly all limitations of current optical probes and sensors, which have run into fundamental chemical and photophysical incompatibilities with living systems. (Schuck)

Mass radiological triage is critical after a large-scale radiological event because of the need to identify those individuals who will benefit from medical intervention as soon as possible. The goal of the ongoing NIH-funded research project is to design a prototype of a fully automated, ultra high throughput biodosimetry. This prototype is supposed to accommodate multiple assay preparation protocols that allow the determination of the levels of radiation exposure that a patient received. The input to this fully autonomous system is a large number of capillaries filled with blood of patients collected using finger sticks. These capillaries are processed by the system to distill the micronucleus assay in lymphocytes, with all the assays being carried out in situ in multiwell plates. The research effort on this project involves the automation system design and integration including hierarchical control algorithms, design and control of custom built robotic devices, and automated image acquisition and processing for sample preparation and analysis. (Yao)

A technology that couples the power of multidimensional microscopy (three spatial dimensions, time, and multiple wavelengths) with that of DNA array technology is investigated in an NIH-funded project. Specifically, a system is developed in which individual cells selected on the basis of optically detectable multiple features at critical time points in dynamic processes can be rapidly and robotically micromanipulated into reaction chambers to permit amplified DNA synthesis and subsequent array analysis. Customized image processing and pattern recognition techniques are developed, including Fisher's linear discriminant preprocessing with neural net, a support vector machine with improved training, multiclass cell detection with error correcting output coding, and kernel principal component analysis. (Yao)

Facilities for Teaching and Research

The undergraduate laboratories, occupying an area of approximately 6,000 square feet of floor space, are the site of experiments ranging in complexity from basic instrumentation and fundamental exercises to advanced experiments in such diverse areas as automatic controls, heat transfer, fluid mechanics, stress analysis, vibrations, microcomputer-based data acquisition, and control of mechanical systems.

Equipment includes microcontrollers and microprocessors, analog-to-digital and digital-to-analog converters, a tensile testing system equipped with digital image correlation (DIC) capabilities, a subsonic wind tunnel, and 3D printers as well as laser cutters. The undergraduate laboratory also houses experimental setups for the understanding and performance evaluation of a small steam power generation system, a heat exchanger, a compressor, a car suspension simulator, a torsion tester, and a hydrogen fuel cell. Part of the undergraduate laboratory is a staffed machine shop with machining tools such as CNC vertical milling machines, a CNC lathe, standard vertical milling machines, engine and bench lathes, surface grinder, band saw, drill

MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
STANDARD TRACK

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) **and** ORCA E2500 (3)[6] either semester	
				APMA E2101 (3)[1] **or** Linear Algebra (3)[2] **and** ODE (3)[3]
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	UN1403 (3)[4] UN2601 (3.5)[4]	
CHEMISTRY	one semester lecture (3–4) UN1403 **or** UN1404 **or** UN2045 **or** UN1604	Lab UN1500 (3)[5]		
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL COURSES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4) HUMA UN1121 **or** UN1123 (3)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4) ECON UN1105 (4) **and** UN1155 recitation (0)
REQUIRED TECHNICAL COURSES				ENME E3105 (4)
COMPUTER SCIENCE	Computer language: COMS W1004 or COMS W1005 (3) or ENGI E1006 (3) (in semester I or III)			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] Students who take APMA E2101 must complete an additional 3 point course in math or basic science with one of the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, or EEEB. One technical elective 3000-level or higher), with the approval of your ME faculty adviser, may be substituted for this purpose.

[2] Linear algebra may be fulfilled by either APMA E3101 or MATH UN2010.

[3] Ordinary differential equations may be fulfilled by either MATH UN2030 or MATH UN3027.

[4] May substitute EEEB UN2001, BIOL UN2005, or higher.

[5] May substitute Physics Lab UN1494 (3) or UN3081 (2).

[6] Offered in spring semester.

press, tool grinders, a horizontal bandsaw, several other mills used for light machining and circuit board fabrication.

A mechatronics laboratory affords the opportunity for hands-on experience with microcomputer-embedded control of electromechanical systems. Facilities for the construction and testing of analog and digital electronic circuits aid the students in learning the basic components of the microcomputer architecture. The laboratory is divided into work centers for two-person student laboratory teams. Each work center is equipped with a mixed signal oscilloscope, several power supplies (for low-power electronics and higher power control), a function generator, a multimeter, a protoboard for building circuits, a microcomputer circuit board (which includes the microcomputer and peripheral components), a microcomputer programmer, and a personal computer that contains a data acquisition board. The data acquisition system serves as an oscilloscope, additional function generator, and spectrum analyzer for the student team. The computer also contains a complete microcomputer software development system, including editor, assembler, simulator, debugger, and C compiler.

MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS
STANDARD TRACK

	SEMESTER V	**SEMESTER VI**	**SEMESTER VII**	**SEMESTER VIII**
REQUIRED COURSES	MECE E3018 (3) Lab I MECE E3100 (3) Fluids I MECE E3301 (3) Thermodynamics MECE E3408 (3) Graphics and design MECE E3414 (3)[1] Mechanics of solids for mechanical engineers	MECE E3028 (3) Lab II ENME E3106 (3) Dynamics and vibrations MECE E3311 (3) Heat transfer MECE E3610 (3) Materials and processes in manufacturing ELEN E1201 (3.5)[2] Intro. elec. eng.	MECE E3409 (3) Machine design MECE E3420 (3) Engineering design: concept	MECE E3430 (3) Engineering design: creation EEME E3601 (3) Classical control sys.
	MECE E1008 (1) Intro to machining (either semester)			
TECHNICAL ELECTIVES[3]		9 points[5]		
NONTECH ELECTIVES[4]	Students must complete the 27-point requirement.[6]			
TOTAL ESTIMATED POINTS[7]	15–16	16.5–19.5	12–15	12

[1] Required for class of 2025 and beyond.

[2] Strongly recommended to be taken in Semester III or IV.

[3] 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 one of the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, or EEEB. One technical elective (3000-level or higher), with the approval of your ME faculty adviser, may be substituted for this purpose.

[4] Not required for Combined Plan students.

[5] 9 points required; 6 must be MECE courses.

[6] See page 9; not required for Combined Plan students.

[7] Students must complete a minimum of 128 points to graduate.

The laboratory is also equipped with a portable oscilloscope, an EPROM eraser (to erase microcomputer programs from the erasable chips), a logic probe, and an analog filter bank that the student teams share, as well as a stock of analog and digital electronic components.

The CAD Lab is a modern computer-aided design laboratory equipped with 30 Dell Precision 5820 workstations. Machines have software for design, CAD, FEM, and CFD, including Altair Analysis Suite, AutoCAD, COMSOL Multiphysics, Matlab, RStudio, Solidworks, Wolfram Mathematica. The research facilities are located within within individual or group research laboratories in the department, and these facilities are being continually upgraded. To view the current research capabilities please visit the various laboratories within the research section of the department website. The students and staff of the department can, by prior arrangement, use much of the equipment in these research facilities. Through their participation in the NSF-MRSEC center, the faculty also have access to shared instrumentation and the clean room located in the Schapiro Center for Engineering and Physical Science Research. Columbia University's extensive library system has superb scientific and technical collections.

Email and computing services are maintained by Columbia University Information Technology (CUIT). For more information visit columbia.edu/cuit.

UNDERGRADUATE PROGRAM

The Mechanical Engineering Undergraduate Program at Columbia University has the following Program Educational Objectives (PEOs) for its graduates:

1. Practice mechanical engineering in a broad range of industries.
2. Pursue advanced education, research and development, and other creative and innovative efforts in science, engineering, and technology, as well as other professional careers.
3. Conduct themselves in a responsible, professional, and ethical manner.
4. Participate in activities that support humanity and economic development nationally and globally, developing as leaders in their fields of expertise.

As stated on the Mechanical

MECHANICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS
EARLY DECISION TRACK

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH UN1101 (3)	MATH UN1102 (3)	APMA E2000 (4) and E2001 (0) **and** ORCA E2500 (3)[6] either semester	
				APMA E2101 (3)[1] **or** Linear Algebra (3)[2] **and** ODE (3)[3]
PHYSICS (three tracks, choose one)	UN1401 (3) UN1601 (3.5) UN2801 (4.5)	UN1402 (3) UN1602 (3.5) UN2802 (4.5)	UN1403 (3)[4] UN2601 (3.5)[4]	
CHEMISTRY	one semester lecture (3–4) UN1403 **or** UN1404 **or** UN2045 **or** UN1604	Lab UN1500 (3)[5]		
UNIVERSITY WRITING	CC1010 (3) either semester			
REQUIRED NONTECHNICAL COURSES			HUMA CC1001, COCI CC1101, **or** Global Core (3–4)	HUMA CC1002, COCI CC1102, **or** Global Core (3–4)
REQUIRED TECHNICAL COURSES		ENME E3105 (4) Mechanics	MECE E3414 (3)[7] Mechanics of solids for mechanical engineers	ELEN E1201 (3.5) Intro. to elec. eng. MECE E3408 (3) Graphics and design
COMPUTER SCIENCE	Computer language: COMS W1004 or COMS W1005 (3) or ENGI E1006 (3) (in semester I and III)			
PHYSICAL EDUCATION	UN1001 (1)	UN1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] Students who take APMA E2101 must complete an additional 3 point course in math or basic science with one of the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, or EEEB. One technical elective (3000-level or higher), with the approval of your ME faculty adviser, may be substituted for this purpose.

[2] Linear algebra may be fulfilled by either APMA E3101 or MATH UN2010.

[3] Ordinary differential equations may be fulfilled by either MATH UN2030 or MATH UN3027.

[4] May substitute EEEB UN2001, BIOL UN2005, or higher.

[5] May substitute Physics Lab UN1494 (3) or UN3081 (2).

[6] Offered in spring semester.

[7] Required for class of 2025 and beyond.

Engineering department website, graduates of the Mechanical Engineering program at Columbia University will attain:

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

MECHANICAL ENGINEERING: THIRD AND FOURTH YEARS
EARLY DECISION TRACK

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
REQUIRED COURSES	MECE E3018 (3) Lab I MECE E3100 (3) Fluids I MECE E3301 (3) Thermodynamics	MECE E3028 (3) Lab II ENME E3106 (3) Dynamics and vibrations MECE E3311 (3) Heat transfer MECE E3610 (3) Materials and processes in manufacturing	MECE E3409 (3) Machine design MECE E3420 (3) Engineering design: concept	MECE E3430 (3) Engineering design: creation EEME E3601 (3) Classical control systems
	MECE E1008 (1) Intro to machining (either semester)			
REQUIRED NONTECHNICAL COURSES	HUMA UN1121 **or** UN1123 (3)	ECON UN1105 (4) **and** UN1155 recitation (0)		
TECHNICAL ELECTIVES[1]		9 points [3]		
NONTECH ELECTIVES	Students must complete the 27-point requirement.[4]			
TOTAL ESTIMATED POINTS[2]	12–16	16–19	12–15	12

[1] If APMA E2101 is taken instead of Linear Algebra and ODE, students must complete an additional 3-point course in math or basic science with one of the following course designators: MATH, PHYS, CHEM, BIOL, STAT, APMA, or EEEB. One technical elective (3000-level or higher), with the approval of your ME faculty adviser, may be substituted for this purpose.

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

[3] 9 points required; 6 must be MECE courses.

[4] See page 9; not required for Combined Plan students.

appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Highly qualified students are permitted to pursue an honors course consisting of independent study under the guidance of a member of the faculty.

Upon graduation the student may wish to enter employment in industry or government, or continue with graduate study. Alternatively, training in mechanical engineering may be viewed as a basis for a career in business, patent law, medicine, or management. Thus, the department's undergraduate program provides a sound foundation for a variety of professional endeavors.

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

Undergraduates who wish to declare mechanical engineering as their major should do so prior to the start of their junior year. Students who declare in their first year should follow the Early Decision Track. Students who declare in their second year should follow the Standard Track. Students who wish to declare during or after the fall semester of their junior year must first obtain approval from the Mechanical Engineering Department.

Of the 18 points of elective content in the third and fourth years, at least 9 points of technical elective courses, including at least 6 points from the Department of Mechanical Engineering, must be taken. A technical elective can be any engineering course offered in the SEAS bulletin that is 3000 level or above. Those prior remaining points of electives are intended primarily as an opportunity to complete the four-year, 27-point nontechnical requirement. Consistent with professional accreditation standards, courses in engineering science and courses in design must have a combined credit of 45 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 E4200) as well as a course in numerical methods (APAM E3105 or APMA E4300) as technical electives. Ideally, planning for these courses should start at the beginning of the sophomore year.

Fundamentals of Engineering (FE) Exam

The FE exam is a state licensing exam and the first step toward becoming a Professional Engineer (P.E.). P.E. licensure is important for engineers to obtain—it shows a demonstrated commitment to professionalism and an established record of abilities that will help a job candidate stand out in the field. Ideally, the FE exam should be taken in the senior year while the technical material learned while pursuing the undergraduate degree is still fresh in the student's mind. In addition to the FE exam, achieving P.E. licensure requires some years of experience and a second examination, which tests knowledge gained in engineering practice. For more information, please see http://ncees.org/exams/fe-exam.

The Mechanical Engineering Department strongly encourages all seniors to take this exam and offers a review course covering material relevant to the exam, including a practice exam to simulate the testing experience. The FE exam is given in the fall and spring of each year. The review course is offered in the spring semester, concluding before the spring exam.

Integrated B.S./M.S. Program

The Integrated B.S./M.S. degree program is open to a qualified group of Columbia juniors and makes possible the earning of both the B.S. and M.S. degree in an integrated fashion. Benefits of this program include optimal matching of graduate courses with corresponding undergraduate prerequisites, greater ability to plan ahead for most advantageous course planning, opportunities to do research for credit during the summer after senior year, and up to 6 points of 4000-level technical electives from the B.S. requirement may count toward the fulfillment of the point requirement of the M.S. degree. Additional benefits include simplified application process, no GRE is required, and no reference letters are required. To qualify for this program, students must have a cumulative GPA of at least 3.4 and strong recommendations from within the Department. Students should apply for the program by April 30 in their junior year. For more information on requirements and access to an application form, please visit me.columbia.edu/integrated-bsms-program.

Express M.S. Application

The Express M.S. Application is offered to current seniors, including 3-2 students, who are enrolled in the BS program. In the Express M.S. Application, a master's degree can be earned seamlessly. Graduate classes are available for seniors to apply toward their M.S. degree and the advanced courses that will be taken have been designed to have the exact prerequisites completed as an undergraduate. Other advantages include the opportunity for better course planning and creating a streamlined set of courses more possible. Additional benefits include simplified application process, no GRE is required and no reference letters are required. To qualify for this program, your cumulative GPA should be at least 3.5. For more information on requirements and access to an application, please visit me.columbia.edu/ms-express-application-1.

Barnard 4+1 Mechanical Engineering Pathways - Physics

The Barnard 4+1 Pathway in Physics is offered to current Barnard College juniors with a GPA of 3.5 or higher to apply to Master's programs in Civil Engineering, Electrical Engineering, and Mechanical Engineering. Students should inquire with Beyond Barnard and plan on attending an introductory information sessions for the unique 4+1 Pathway they may be interested in pursuing.
Faculty contact at Barnard: Professor Reshmi Mukherjee, rmukherj@barnard.edu; at SEAS: Professor Gerard Ateshian, gaa3@columbia.edu

GRADUATE PROGRAMS

The Department of Mechanical Engineering offers two doctoral degrees: Doctor of Philosophy (Ph.D.) and Doctor of Engineering Science (Eng.Sc.D.), and the Master of Science degree. The Ph.D. degree is conferred by the Graduate School of Arts and Science, and the Eng.Sc.D. degree is conferred by The Fu Foundation School of Engineering and Applied Science.

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

Master of Science Degree Program

The program leading to the Master of Science degree in mechanical engineering requires completion of a minimum of 30 points of approved coursework consisting of no fewer than ten courses. A thesis based on either experimental, computational, or analytical research is optional and may be counted in lieu of up to 6 points of coursework. In general, attainment of the degree requires one academic year of full-time study, although it may also be undertaken on a part-time basis, for domestic students, over a correspondingly longer period. A minimum grade-point average of 2.5 is required for graduation.

The M.S. degree in mechanical engineering allows a student to take a sequence of courses tailored to their interests and objectives; this is referred to as the standard track. Alternatively, M.S. students can pick from a set of predefined tracks.

Typical choices in the standard track include such subjects as mechanics of solids and fluids, thermodynamics, heat transfer, manufacturing engineering, robotics, kinematics, dynamics and vibrations, controls, and power generation. Nevertheless, the following guidelines must be adhered to:

1. All courses must be at the graduate level, i.e., numbered 4000 or higher, with at least two 6000-level lecture courses in SEAS. At least one of the 6000-level courses must be in Mechanical Engineering.
2. Every program must contain at least

one course in mathematics (APMA, MATH, STAT course designations) covering material beyond what the student has taken previously. It is recommended to be taken early in the sequence, in order to serve as a basis for the technical coursework. Alternatively, any one of the following courses may be taken to satisfy the math requirement: BMEN E4110 Biostatistics; COMS W4701 Artificial intelligence; COMS W4771 Machine learning; IEOR E4150* (same as STAT GU4001); MECE E4520 Data science for mechanical engineers; and ORCA E4500 Foundations of data science

3. Out-of-department study is encouraged, but must be taken in consultation with a faculty adviser.
4. At least five courses must be in Mechanical Engineering.

Students who are not on the standard track can select a concentration in either biomechanics, energy systems, micro/nanoscale engineering, or robotics and control. The requirements for a concentration are identical to those of the standard track, with one exception: students must take at least 15 points from a list determined by an adviser in consultation with an advisory committee. The currently available concentrations are listed below.

M.S. in Mechanical Engineering with Concentration in Biomechanics

Advisers: Professors Gerard Ateshian, Karen Kasza, Kristin Myers, and Vijay Vedula

The concentration in biomechanics is developed in coordination with the Department of Biomedical Engineering. It provides the M.S. candidate with knowledge of the mechanics of biological tissues. The 4000-level courses offered in this concentration provide foundations of fluid and solid mechanics applicable to biomechanics, as well as applications of mechanics to specific cell, tissue, and organ systems. The higher-level courses provide deeper foundations on theoretical and computational approaches relevant to biomechanics. This concentration is a suitable preparation for careers in the biomedical devices industry or engineering and scientific consulting.

To choose this concentration, select "Mechanical Engineering Biomechanics Master of Science" in the Program field when filling in the online application for the M.S. program. The name of this program will be listed on graduates' transcripts.

Requirements: While satisfying the requirements for a Master of Science in Mechanical Engineering, take at least five courses from:

MEBM E4703: Molecular mechanics in biology
MEBM E4710: Morphogenesis: shape and structure in biological materials
MECE E4100: Mechanics of fluids
MECE E6100: Advanced mechanics of fluids
MECE E6106: Finite element method for fluid flow and fluid-structure interactions
MEBM E6310–E6311: Mixture theories for biological tissues I and II
MECE E6422–E6423: Introduction to the theory of elasticity I and II
MECE E8501: Advanced continuum biomechanics

When offered by the Biomedical Engineering Department, the following courses may also count toward the Biomechanics track:

BMEN E4301: Structure, mechanics, and adaptation of bone
BMEN E4302: Biomechanics of musculoskeletal soft tissues
BMEN E4305: Cardiac mechanics
BMEN E4310: Solid biomechanics
BMEN E4320: Fluid biomechanics
BMEN E4340: Biomechanics of cells
BMEN E4350: Biomechanics of developmental biology
BMEN E4570: Science and engineering of body fluids
BMEN E4750: Sound and hearing
BMEN E6301: Modeling of biological tissues with finite elements
BMME E4702: Advanced musculoskeletal biomechanics

One 3-credit research course can be counted toward the concentration if the research is approved by the student's adviser and is biomechanics related.

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

Advisers: Professors Michael Burke, Vijay Modi, and Arvind Narayanaswamy

The concentration in energy systems provides the M.S. candidate with a global understanding of current energy challenges. Advanced thermofluidic knowledge is provided to design and optimize energy systems, with a strong emphasis on renewable energies. Courses related to energy and environmental policy, two strong areas of Columbia as a global university, can be integrated into the course sequence. This specialization is a suitable preparation for careers in energy production and energy consultation.

Requirements: While satisfying the requirements for a Master of Science in Mechanical Engineering, take at least five courses from:

MECE E4210: Energy infrastructure planning
MECE E4211: Energy sources and conversion
MECE E4302: Advanced thermodynamics
MECE E4304: Turbomachinery
MECE E4305: Mechanics and thermodynamics propulsion
MECE E4312: Solar thermal engineering
MECE E4314: Energy dynamics of green buildings
MECH E4320: Intro to combustion
MECE E4330: Thermofluid systems design
MECE E6100: Advanced mechanics of fluids
MECE E6104: Case studies in computational fluid dynamics
MECE E6313: Advanced heat transfer
EAEE E6126: Carbon sequestration

Furthermore, students must take one course in statistics (STAT or SIEO designations). One 3-credit research course can be counted toward the concentration if the research is approved by the student's adviser and is energy related.

M.S. in Mechanical Engineering with Concentration in Micro/Nanoscale Engineering

Advisers: Professors James Hone, Jeffrey Kysar, and P. James Schuck

The concentration in micro/nanoscale engineering provides the M.S. candidate with an understanding of engineering challenges and opportunities in micro- and nanoscale systems. The curriculum addresses fundamental issues of mechanics, fluid mechanics, optics, heat transfer, and manufacturing at small-size scales. Application areas include MEMS, bio-MEMS, microfluidics, thermal systems, and carbon nanostructures.

Requirements: The requirements for the micro/nanoscale engineering track ensures that students obtain an education in micro/nanoscale engineering that is both broad and deep. Students will be required to take at least five classes from a selected pool that covers many aspects of micro/nanoengineering. Currently, eight classes are compatible with the general requirements for the Master of Science degree in Mechanical Engineering. These include:

MECE E4058: Mechatronics
MECE E4212: Microelectromechanical systems (MEMS)
MECE E4213: BioMEMS
MECE E4214: MEMS production and manufacturing
MECE E6137: Nanoscale actuation and sensing
MECE E6432: Small scale mechanical behavior

When offered by other departments, the following courses may also count toward the micro/nanoscale concentration:

APPH E6081: Solid state physics 1
ELEN E4106: Advanced solid state device materials
ELEN E4411: Fundamentals of photonics
ELEN E4944: Principles of device microfabrication
ELEN E6331: Principles semiconductor physics
ELEN E6414: Photonic integrated circuits
ELEN E6945: Device nano fabrication
MSAE E4090: Nanotechnology
MSAE E4100: Crystallography
PHYS W4018: Solid state physics

One 3-credit research course can be counted toward the concentration if the research is approved by the student's adviser and is micro/nanoscale related.

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

Advisers: Professors Sunil Agrawal, Matei Ciocarlie, and Hod Lipson

The field of robotics is seeing unprecedented growth, in areas as diverse as manufacturing, logistics, transportation, health care, space exploration, and more. This program prepares students for a career in robotics and its many applications in society. Students perform in-depth study of topics such as robotic manipulation, navigation, perception, human interaction, medical robotics, assistance and rehabilitation. This specialization is a suitable preparation for joining established companies, information-age dominant players investing heavily in this field, or the new wave of robotics start-ups aiming to provide disruptive innovations. Many of the acquired skills can be applied in other fields as diverse as automation, manufacturing, computer graphics or machine vision. This program can also be a foundation for a research career in robotics and related areas, in both academia and industry.

Requirements: While satisfying the requirements for a Master of Science in Mechanical Engineering, take at least five courses from:

MECE E4058: Mechatronics and embedded microcomputer control
MECE E4602: Intro to robotics
MECE E4606: Digital manufacturing
MECE E4611: Robotics studio
MECE E6400: Advanced machine dynamics
MECE E6614: Advanced topics in robotics and mechanism synthesis
MECS E4510: Design automation
MECS E6615: Robotic manipulation
MECS E6616: Robot learning
EEME E4601: Digital control systems
EEME E6601: Introduction to control theory
EEME E6602: Modern control theory
EEME E6610: Optimal control theory
ELEN E4810: Digital signal processing
BMME E4702: Advanced musculoskeletal biomechanics

When offered by the Computer Science Department, these courses may also be used to satisfy the robotics requirements:

COMS W4731: Computer vision
COMS W4733: Computational aspects of robotics
COMS E6733: 3D photography*

One 3-credit research course can be counted toward the concentration if the research is approved by the student's adviser and is robotics related.

Doctoral Degree Program

All applications to the doctoral program in mechanical engineering are administered by The Fu Foundation School of Engineering and Applied Science. Students who matriculate into the doctoral program without a master's degree earn a Master of Science degree while pursuing their doctoral degree.

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

Program Requirements

- 30 credits beyond master's degree
- GPA of 3.2 or better in graduate courses
- 4 semesters of graduate seminar MECE E9500
- Completion of all milestones
- Completion of two semesters teaching experience each equivalent to 20hrs/week effort

See me.columbia.edu/academics doctoral-program for more information.

COURSES IN MECHANICAL ENGINEERING

MECE E1001x Mechanical engineering: micromachines to jumbo jets
3 pts. Lect: 3. Not offered in 2024–2025.
Corequisite(s): MATH UN1101 Calculus I. The role of Mechanical Engineering in developing many of the fundamental technological advances on which today's society depends. Topics include airplanes, automobiles, robots, modern manufacturing methods as well as the emerging fields of micro-electromechanical machines (MEMS) and nanotechnology. The physical concepts that govern the operation of these technologies will be developed from basic principles and then applied in simple design problems. Students will also be exposed to state-of-the art innovations in each case study.

MECE E1008x or y Introduction to machining
1 pt. Instructor to be announced.
Introduction to the manual machine operation, CNC fabrication and usage of basic hand tools, band/hack saws, drill presses, grinders and sanders.

MECE E1304x or y Naval ship systems, I
3 pts. Lect: 3. Not offered in 2024–2025.
Students are strongly advised to consult with the ME Department prior to registering for this course. A study of ship characteristics and types including ship design, hydrodynamic forces, stability, compartmentation, propulsion, electrical and auxiliary systems, interior communications, ship control, and damage control; theory and design of steam, gas turbine, and nuclear propulsion; shipboard safety and firefighting. This course is part of the Naval ROTC program at Columbia but will be taught at SUNY Maritime. Enrollment may be limited; priority is given to students participating in Naval ROTC. Will not count as a technical elective. Students should see a faculty adviser as well as Columbia NROTC staff (nrotc@columbia.edu) for more information.

MECE E3018x Mechanical engineering laboratory, I
3 pts. Lect: 3. Professor Yesilevskiy.
Experiments in instrumentation and measurement: optical, pressure, fluid flow, temperature, stress, and electricity; viscometry, cantilever beam, digital data acquisition. Probability theory: distribution, functions of random variables, tests of significance, correlation, ANOVA, linear regression.

MECE E3028y Mechanical engineering laboratory, II
3 pts. Lect: 3. Professor Lin.
Experiments in engineering and physical phenomena: aerofoil lift and drag in wind tunnels, laser Doppler anemometry in immersed fluidic channels, supersonic flow and shock waves, Rankine thermodynamical cycle for power generation, and structural truss mechanics and analysis.

MECE E3100x Introduction to mechanics of fluids
3 pts. Lect: 3. Professor Kasza or Vedula.
Prerequisite(s): ENME E3105. Basic continuum concepts. Liquids and gases in static equilibrium. Continuity equation. Two-dimensional kinematics. Equation of motion. Bernoulli's equation and applications. Equations of energy and angular momentum. Dimensional analysis. Two-dimensional laminar flow. Pipe flow, laminar, and turbulent. Elements of compressible flow.

ENME E3105x and y Mechanics
4 pts. Lect: 4. Professor Kysar.
Prerequisite(s): PHYS UN1401 and MATH UN1101, UN1102, and UN1201 or APMA E2000. Elements of statics, dynamics of a particle, and systems of particles.

MECE E3301x Thermodynamics
3 pts. Lect: 3. Professor Burke or Narayanaswamy.
Classical thermodynamics. Basic properties and concepts, thermodynamic properties of pure substances, equation of state, work, heat, the first and second laws for flow and nonflow processes, energy equations, entropy, and irreversibility. Introduction to power and refrigeration cycles.

MECE E3311y Heat transfer
3 pts. Lect: 3. Professor Burke or Narayanaswamy.
Steady and unsteady heat conduction. Radiative heat transfer. Internal and external forced and free convective heat transfer. Change of phase. Heat exchangers.

MECE E3401x Mechanics of machines
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): ENME E3105 and MECE E3408. Introduction to mechanisms and machines, analytical and graphical synthesis of mechanism, displacement analysis, velocity analysis, acceleration analysis of linkages, dynamics of mechanism, cam design, gear and gear trains, and computer-aided mechanism design.

MECE E3408x and y Computer graphics and design
3 pts. Lect: 3. Professor Vukelic.
Introduction to drafting, engineering graphics, computer graphics, solid modeling, and mechanical engineering design. Interactive computer graphics and numerical methods applied to the solution of mechanical engineering design problems.

MECE E3409x Machine design
3 pts. Lect: 3. Professor Yesilevskiy.
Prerequisite(s): MECE E3408. Computer-aided analysis of general loading states and deformation of machine components using singularity functions and energy methods. Theoretical introduction to static failure theories, fracture mechanics, and fatigue failure theories. Introduction to conceptual design and design optimization problems. Design of machine components such as springs, shafts, fasteners, lead screws, rivets, welds. Modeling, analysis, and testing of machine assemblies for prescribed design problems. Problems will be drawn from statics, kinematics, dynamics, solid modeling, stress analysis, and design optimization.

MECE E3411y Fundamentals of engineering
1 pt. Lect: 3. Professor Vukelic.
Prerequisite(s): Senior standing. Review of core courses in mechanical engineering, including mechanics, strength of materials, fluid mechanics, thermodynamics, heat transfer, materials and processing, control, and mechanical design and

analysis. Review of additional topics, including engineering economics and ethics in engineering. The course culminates with a comprehensive examination, similar to the Fundamentals of Engineering examination. Meets the first 4.5 weeks only.

MECE E3414x Mechanics of solids for mechanical engineers
3 pts. Lect: 3. Professors Ateshian, Kysar, and Myers.
Prerequisite(s): Mechanics, linear algebra, ordinary differential equations. Introduction to the mechanics of solids with an emphasis on mechanical engineering applications. Stress tensor, principal stresses, maximum shear stress, stress equilibrium, infinitesimal strain tensor, Hooke's law, boundary conditions. Introduction to the finite element method for stress analysis. Static failure theories, safety factors, fatigue failure. Assignments include finite element stress analyses using university-provided commercial software.

MECE E3420x Engineering design—concept/design generating
3 pts. Lect: 3. Professor Yesilevskiy.
Prerequisite(s): Senior standing. Corequisite(s): MECE E3409. A preliminary design for an original project is a prerequisite for the capstone design course. Will focus on the steps required for generating a preliminary design concept. Included will be a brainstorming concept generation phase, a literature search, incorporation of multiple constraints, adherence to appropriate engineering codes and standards, and the production of a layout drawing of the proposed capstone design project in a Computer Aided Design (CAD) software package. Note: MECE students only.

MECE E3430y Engineering design
3 pts. Lect: 2. Lab: 4. Professor Yesilevskiy.
Prerequisite(s): MECE E3420. Building on the preliminary design concept, the detailed elements of the design process are completed: systems synthesis, design analysis optimization, incorporation of multiple constraints, compliance with appropriate engineering codes and standards, and Computer Aided Design (CAD) component part drawings. Execution of a project involving the design, fabrication, and performance testing of an actual engineering device or system.

MECE E3450x or y Computer-aided design
3 pts. Lect: 3. Professor Ateshian or Myers.
Prerequisite(s): ENME E3105, E3113, MECE E3408, E3311. Introduction to numerical methods and their applications to rigid body mechanics for mechanisms and linkages. Introduction to finite element stress analysis for deformable bodies. Computer-aided mechanical engineering design using established software tools and verifications against analytical and finite difference solutions.

EEME E3601y Classical control systems
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): MATH UN2030. Analysis and design of feedback control systems. Transfer functions; block diagrams; proportional, rate, and integral controllers; hardware, implementation. Routh stability criterion, root locus, Bode and Nyquist plots, compensation techniques.

MECE 3610y Materials and processes in manufacturing
3 pts. Lect: 3. Professor Yao.
Prerequisite(s): ENME E3113 or the equivalent. Introduction to microstructures and properties of metals, polymers, ceramics and composites; typical manufacturing processes: material removal, shaping, joining, and property alteration; behavior of engineering materials in the manufacturing processes.

MECE E3899x and y Undergraduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

MECE E3900x-E3901y Honors tutorial in mechanical engineering
3 pts. Lect: 3. Members of the faculty.
Prerequisite(s): 3.2 or higher GPA. Individual study; may be selected after the first term of the junior year by students maintaining a 3.2 grade-point average. Course format may vary from individual tutorial to laboratory work to seminar instruction under faculty supervision. Projects requiring machine-shop use must be approved by the laboratory supervisor. Students may count up to 6 points toward degree requirements. Students must submit both a project outline prior to registration and a final project write up at the end of the semester.

MECE E3998x and y Projects in mechanical engineering
1–3 pts. Members of the faculty.
Prerequisite(s): Approval by faculty member who agrees to supervise the work. Independent project involving theoretical, computational, experimental, or engineering design work. May be repeated, but no more than 3 points may be counted toward degree requirements. Projects requiring machine-shop use must be approved by the laboratory supervisor. Students must submit both a project outline prior to registration and a final project write-up at the end of the semester.

MECE E3999x, y or s Fieldwork
1–2 pts. Professor Myers.
Prerequisite(s): Obtained internship and approval from a faculty adviser. May be repeated for credit, but no more than 3 total points may be used toward the 128-credit degree requirement. Only for MECE undergraduate students who include relevant on-campus and 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 requirements. May not be taken for pass/fail credit or audited.

MECE E4058x and y Mechatronics and embedded microcomputer control
3 pts. Lect: 3. Professor Zordan.
Prerequisite(s): ELEN E1201. Recommended: ELEN E3000. Enrollment limited to 12 students. Mechatronics is the application of electronics and microcomputers to control mechanical systems. Systems explored include on/off systems, solenoids, stepper motors, DC motors, thermal systems, magnetic levitation. Use of analog and digital electronics and various sensors for control. Programming microcomputers in Assembly and C. Lab required.

MECE E4078x or y Internet of (Mechanical) Things
3 pts. Lect: 3.
Hands-on, project-oriented course covering foundations of Internet of Things (IoT) technologies as they relate to the physical world. Projects utilizing Arduino and Raspberry Pi platforms. End-to-end IoT including sensors, basic controls, embedded systems programming, networking, IoT protocols, power consumption/optimization, and cloud connectivity. Build real IoT devices and systems in two team-based projects.

MECE E4100y Mechanics of fluids
3 pts. Lect: 3. Professor Kasza.
Prerequisite(s): MECE E3100 or equivalent. Fluid dynamics and analyses for mechanical engineering and aerospace applications: boundary layers and lubrication, stability and turbulence, and compressible flow. Turbomachinery as well as additional selected topics.

IEME E4200x or y Introduction to human-centered design
1.5 pts. Lect: 4.5. Professor West.
Prerequisite(s): Application to instructor for approval. Open to SEAS graduate and advanced undergraduate students, Business School, and GSAPP. Students from other schools may apply. Fast-paced introduction to human-centered design. Students learn the vocabulary of design methods, understanding of design process. Small group projects to create prototypes. Design of simple product, more complex systems of products and services, and design of business.

MECE E4210x or y Energy infrastructure planning
3 pts. Lect: 3. Professor Modi.
Prerequisite(s): One year each of college level physics, chemistry, and mathematics. Energy infrastructure planning with specific focus on countries with rapidly growing infrastructure needs. Spatiotemporal characteristics, scale, and environmental footprints of energy resources, power generation and storage, modeling demand growth, technology choices and learning for planning. Computer-assisted decision support and network design/optimization tools. Similarities, differences and interactions among electricity, gas, information, transportation and water distribution networks. Penetration of renewable and/or decentralized technologies into existing or new infrastructure. Special guest lectures on infrastructure finance, regulation and public-private partnerships.

MECE E4211x or y Energy: sources and conversion
3 pts. Lect: 3. Professor Modi.
Prerequisite(s): MECE E3301. Energy sources such as oil, gas, coal, gas hydrates, hydrogen, solar, and wind. Energy conversion systems for

electrical power generation, automobiles, propulsion and refrigeration. Engines, steam and gas turbines, wind turbines; devices such as fuel cells, thermoelectric converters, and photovoltaic cells. Specialized topics may include carbon-dioxide sequestration, cogeneration, hybrid vehicles and energy storage devices.

MECE E4212x or y Microelectromechanical systems
3 pts. Lect: 1.5. Lab: 3. Professor Schuck.
MEMS markets and applications; scaling laws; silicon as a mechanical material; Sensors and actuators; micromechanical analysis and design; substrate (bulk) and surface micromachining; computer aided design; packaging; testing and characterization; microfluidics.

MECE E4213x or y Biomicroelectromechanical systems (BioMEMS): design, fabrication, and analysis
3 pts. Lect: 3. Professor Lin.
Prerequisite(s): MECE E3100 and E3311, course in transport phenomena, or instructor's permission. Silicon and polymer micro/nanofabrication techniques; hydrodynamic microfluidic control; electrokinetic microfluidic control; microfluidic separation and detection; sample preparation; micro bioreactors and temperature control; implantable MEMS, including sensors, actuators and drug delivery devices.

MECE E4214x or y MEMS sensors and systems
3 pts. Lect: 3. Professor Hilton.
Prerequisite(s): MECE E4212. Connects basic MEMS transduction elements to applications by analyzing the analog signal chain, sensor packaging, and sensor integration into larger systems. Underlying concepts of analog instrumentation such as filtering and digitization covered. Hands-on projects involve off-the-shelf sensors and single-board computers to create self-contained sensor systems that demonstrate relevant issues.

MECE E4302y Advanced thermodynamics
3 pts. Lect: 3. Professor Burke.
Prerequisite(s): MECE E3301. Advanced classical thermodynamics. Availability, irreversibility, generalized behavior, equations of state for nonideal gases, mixtures and solutions, phase and chemical behavior, combustion. Thermodynamic properties of ideal gases. Applications to automotive and aircraft engines, refrigeration and air conditioning, and biological systems.

MECE E4304x Turbomachinery
3 pts. Lect: 3. Not offered in 2024–2025.
Introduces the basics of theory, design, selection and applications of turbomachinery. Turbomachines are widely used in many engineering applications such as energy conversion, power plants, air-conditioning, pumping, refrigeration and vehicle engines, as there are pumps, blowers, compressors, gas turbines, jet engines, wind turbines, etc. Applications are drawn from energy conversion technologies, HVAC and propulsion. Provides a basic understanding of the different kinds of turbomachines.

MECE E4305y Mechanics and thermodynamics of propulsion
3 pts. Lect: 3. Professor Bradshaw.
Prerequisite(s): MECE E3301 and MECE E4306 or instructor approval. Principles of aerospace propulsion. Fundamentals of thermal-fluids engineering. Thermodynamic cycles of air breathing propulsion systems, including ramjet, scramjet, turbojet, and turbofan engines. Aircraft engine and rocket performance characteristics. Turbomachinery, combustion system, and rocket nozzle aerodynamics. Columbia Engineering interdisciplinary course.

MECE E4306x or y Introduction to aerodynamics
3 pts. Lect: 3. Professor LeVoci.
Principles of flight, incompressible flows, compressible regimes. Inviscid compressible aerodynamics in nozzles (wind tunnels, jet engines), around wings (aircraft, space shuttle) and around blunt bodies (rockets, reentry vehicles). Physics of normal shock waves, oblique shock waves, and explosion waves.

IEME E4310x The manufacturing enterprise
3 pts. Lect: 3. Not offered in 2024–2025.
The strategies and technologies of global manufacturing and service enterprises. Connections between the needs of a global enterprise, the technology and methodology needed for manufacturing and product development, and strategic planning as currently practiced in industry.

MECE E4312x Solar thermal engineering
3 pts. Lect: 3. Professor Naraghi.
Prerequisite(s): MECE E3311 (Heat transfer). Fundamentals of solar energy transport: radiation heat transfer, convention, conduction and phase change processes. Heat exchangers and solar collectors: basic methods of thermal design, flow arrangements, effects of variable conditions, rating procedures. Solar energy concentration. Piping Systems: series and parallel arrangements, fluid movers. Thermal response and management of photovoltaic energy conversion. Solar energy storage. Solar cooling, solar thermal power and cogeneration. Applications to the design of solar thermal engineering systems.

MECE E4313x Decarbonizing buildings studio: energy system retrofits at speed and scale
3 pts. Lect: 3. Professor Zuluaga.
Historical co-evolution of building energy systems and fuels. Classifying existing buildings into typologies that are a prevalent combination of building size, age, fuels, equipment, distribution and zoning controls. Fuels, electricity, furnaces, boilers, heat pumps. Overview of common heat and hot water distribution systems. Case-study based approach to evaluate retrofit options for each typology. Considerations of location, staging upgrades, envelope efficiency, retrofit cost structure, paybacks with a view toward decarbonization.

MECE E4314y Energy dynamics of green buildings
3 pts. Lect: 3. Professor Naraghi.
Prerequisite(s): MECE E3301 and E3311. Introduction to analysis and design of heating, ventilating and air-conditioning systems. Heating and cooling loads. Humidity control. Solar gain and passive solar design. Global energy implications. Green buildings. Building-integrated photovoltaics. Roof-mounted gardens and greenhouses. Financial assessment tools and case studies. Open to Mechanical Engineering graduate students only.

MECH E4320x Introduction to combustion
3 pts. Lect: 3. Professor Burke.
Prerequisite(s): Introductory thermodynamics, fluid dynamics, and heat transfer at the undergraduate level or instructor's permission. Thermodynamics and kinetics of reacting flows; chemical kinetic mechanisms for fuel oxidation and pollutant formation; transport phenomena; conservation equations for reacting flows; laminar nonpremixed flames (including droplet vaporization and burning); laminar premixed flames; flame stabilization, quenching, ignition, extinction, and other limit phenomena; detonations; flame aerodynamics and turbulent flames.

MECE E4330x Thermofluid systems design
3 pts. Lect: 3. Professor Bradshaw.
Prerequisite(s): MECE E3100, E3301, E3311. Theoretical and practical considerations, and design principles, for modern thermofluids systems. Topics include boiling, condensation, phase change heat transfer, multimode heat transfer, heat exchangers, and modeling of thermal transport systems. Emphasis on applications of thermodynamics, heat transfer, and fluid mechanics to modeling actual physical systems. Term project on conceptual design and presentation of a thermofluid system that meets specified criteria.

MECE E4350x Building energy modeling and simulation
3 pts. Lect: 3. Professor Howard.
Review of building energy modeling techniques for simulating time-varying demand. Detailed Physics-based models, gray-box and black-box modeling. Static and dynamic models of building energy systems. Deterministic and Stochastic occupancy modeling. Modeling of control and dispatch of HVAC and local energy systems. Implementation of models in Energyplus and Modelica platforms. Modeling of low and net-zero carbon buildings and local energy systems.

MECE E4400x and y Computer laboratory access
0 pts.
Sign up for this class to obtain a computer account and access to the Department of Mechanical Engineering Computer Laboratory.

MECE E4404x or y Tribology: friction, lubrication, and wear
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MECE E3100, E3311, and ENME E3113, or permission of the instructor. Friction, lubrication, and wear between sliding surfaces. Surface metrology, contact mechanics, and sliding friction. Deformation, wear, and temperature rise of nonlubricated, liquid-lubricated, and solid-lubricated rolling and sliding materials. The

theories of boundary, elastohydrodynamic, hydrodynamic, hydrostatic, and solid-phase lubrication. Lubricant flow and load-carrying capacity in bearings. Special applications such as geartrains, cam/tappets, and micro- and nanoscale tribological interfaces.

MECE E4430x Automotive dynamics
3 pts. Lect: 3. Professor Browne.
Prerequisite(s): ENME E3105 or equivalent; Recommended: ENME E3100 or E3106. Reviews fundamentals of vehicle dynamics. A systems-based engineering approach to explore areas of: tire characteristics, aerodynamics, stability and control, wheel loads, ride and roll rates, suspension geometry, and dampers. A high-performance vehicle (racecar) platform used as an example to review topics.

MECE E4431x or y Space vehicle dynamics
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): ENME E3105; ENME E4202 recommended. Space vehicle dynamics and control, rocket equations, satellite orbits, initial trajectory designs from Earth to other planets, satellite attitude dynamics, gravity gradient stabilization of satellites, spin-stabilized satellites, dual-spin satellites, satellite attitude control, modeling, dynamics, and control of large flexible spacecraft.

MEBM E4439x Modeling and identification of dynamic systems
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APMA E2101, ELEN E3801, or corequisite(s) EEME E3601, or permission of instructor. Generalized dynamic system modeling and simulation. Fluid, thermal, mechanical, diffusive, electrical, and hybrid systems are considered. Nonlinear and high order systems. System identification problem and Linear Least Squares method. State-space and noise representation. Kalman filter. Parameter estimation via prediction-error and subspace approaches. Iterative and bootstrap methods. Fit criteria. Wide applicability: medical, energy, others. MATLAB and Simulink environments.

MEBM E4440x Physiological controls
3 pts. Lect: 3. Professor Chbat.
Prerequisite(s): MEBM E4439 and APMA E2101. Fundamentals of time and frequency domains analyses and stability. Frequency domain controller design. Cardiovascular and respiratory systems simulation. Endogenous control systems: baroreflex, chemoreflex, thermoregulation, pupillary light reflex. Open and closed loop physiological systems. Exogenous control systems: ventilators, infusion pumps. Nonlinear actuators and delayed feedback systems. Acute disease simulation and clinical decision support in the intensive care unit. MATLAB and Simulink environments utilized.

MECE E4440x or y Optimization of dynamic systems
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): Course on linear and/or nonlinear control theory, introduction to Robotics, or instructor's permission. Fundamentals for optimizing performance of dynamic systems described by a set of ordinary differential equations based on theory of variational calculus. Systematic methods to solve optimization problems using numerical methods. Topics include: Static Optimization of systems with equality and inequality and inequality constraints, Numerical methods to solve static optimization problems, Theory of calculus of variations, Application of calculus of variations to solve static optimization problems with equality and inequality constraints, numerical methods to solve static optimization problems, theory of calculus variations to solve dynamic optimization problems with equality and inequality constraints, direct and indirect numerical methods to solve dynamic optimization problems, finite-time linear systems, steady state linear systems, multi degree-of-freedom robotic systems.

MECE E4460x Mechanics of elastomeric materials
3 pts. Lect: 3. Professor Boyce.
Prerequisite(s): MECE E3414. Mechanics of non-linear mechanical behavior of elastomeric and elastomeric-like solids. Overview of structure and behavior of elastomers. Kinematics of large deformation. Constitutive models for equilibrium stress-strain behavior, using invariant measures of deformation and statistical mechanics of molecular networks. Hysteretic aspects of structure and behavior due to time dependence and structural evolution with deformation. Review of experimental data and models to capture and predict observations. Time permitting: behavior of particle-filled, thermoplastic and biomacromolecular elastomers.

MECE E4501y Geometrical modeling
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): COMS W1005. Relationship between 3D geometry and CAD/CAM; representations of solids; geometry as the basis of analysis, design, and manufacturing; constructive solid geometry and the CSG tree; octree representation and applications; surface representations and intersections; boundary representation and boundary evaluation; applied computational geometry; analysis of geometrical algorithms and associated data structures; applications of geometrical modeling in vision and robotics.

MECE E4502x Computational geometry for CAD/CAM
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): COMS W1005 FORTRAN or PASCAL. Analysis of geometric problems and the design of efficient methodologies to obtain solutions to these problems. Algorithms to be studied include geometric searching, convex hulls, triangulations, Voronoi diagrams, intersections, hidden surfaces. Emphasis will be on practical aspects of these algorithms, and on applications of the solutions in computer-aided product design and manufacturing.

MECS E4510x Evolutionary computation and design automation
3 pts. Lect: 3. Professor Lipson.
Prerequisite(s): Basic programming experience in any language. Fundamental and advanced topics in evolutionary algorithms and their application to open-ended optimization and computational design. Covers genetic algorithms, genetic programming, and evolutionary strategies, as well as governing dynamic of coevolution and symbiosis. Includes discussions of problem representations and applications to design problems in a variety of domains including software, electronics, and mechanics.

MECE E4520x or y Data science for mechanical systems
3 pts. Lect: 3. Professor Chen.
Prerequisite(s): Knowledge of basic computer programming (e.g., Java, Matlab, Python) or instructor's permission. Introduction to practical application of data science, machine learning, and artificial intelligence and their application in Mechanical Engineering. Review of relevant programming tools necessary for applying data science is provided, as well as detailed review of data infrastructure and database construction for data science. A series of industry case studies from experts in the field of data science will be presented.

EEME E4601y Digital control systems
3 pts. Lect: 3. Professor Beigi.
Prerequisite(s): EEME E3601 or ELEN E3201. Real-time control using digital computers. Solving scalar and state-space difference equations. Discrete equivalents of continuous systems fed by holds. Z-transer functions. Creating closed-loop difference equation models by Z-transform and state variable approaches. The Nyquist frequency and sample rate selection. Classical and modern based digital control laws. Digital system identification.

MECE E4602x Introduction to robotics
3 pts. Lect: 3. Professor Ciocarlie or Agrawal.
Overview of robot applications and capabilities. Linear algebra, kinematics, statics, and dynamics of robot manipulators. Survey of sensor technology: force, proximity, vision, compliant manipulators. Motion planning and artificial intelligence; manipulator programming requirements and languages.

MECS E4603x Applied robotics: algorithms and software
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Fundamental programming skills (e.g., COMS W1002, W1004, W1005, ENGI E1006, or equivalent). Science and systems aspects of Robotics from applied perspective, focusing on algorithms and software tools. Spatial reasoning; tools for manipulating and visualizing spatial relationships. Analysis of robotic manipulators; numerical methods for kinematic analysis. Motion planning, search-based and stochastic approaches. Applications for force and impedance control. Grading based on combination of exams and projects implemented using Robot Operating System (ROS) software framework and executed on real and simulated robotic manipulators.

MECE E4604x Product design for manufacturability
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Manufacturing process, computer graphics, engineering design, mechanical design. General review of product development process; market analysis and product system design;

principles of design for manufacturing; strategy for material selection and manufacturing process choice; component design for machining; casting; molding; sheet metal working and inspection; general assembly processes; product design for manual assembly; design for robotic and automatic assembly; case studies of product design and improvement.

MECE E4606y Digital manufacturing
3 pts. Lect: 3. Professor Lipson.
Prerequisite(s): Basic programming in any language. Additive manufacturing processes, CNC, Sheet cutting processes, Numerical control, Generative and algorithmic design. Social, economic, legal, and business implications. Course involves both theoretical exercises and a hands-on project.

MECE E4609y Computer-aided manufacturing
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Introductory course on manufacturing processes and knowledge of computer-aided design, and mechanical design or instructor's permission. Computer-aided design, free-form surface modeling, tooling and fixturing, computer numeric control, rapid prototyping, process engineering, fixed and programmable automation, industrial robotics.

MECE E4610x Advanced manufacturing processes
3 pts. Lect: 3. Professor Yao.
Prerequisite(s): Introductory course on manufacturing processes, and heat transfer, knowledge of engineering materials, or instructor's permission. Principles of nontraditional manufacturing, nontraditional transport and media. Emphasis on laser assisted materials processing, laser material interactions with applications to laser material removal, forming, and surface modification. Introduction to electrochemical machining, electrical discharge machining and abrasive water jet machining.

MECE E4611x or y Robotics studio
3 pts. Lect: 1. Lab: 4. Professor Lipson.
Prerequisite(s): Knowledge of basic computer programming (e.g., Java, Matlab, Python) or instructor's permission. Hands-on studio class exposing students to practical aspects of the design, fabrication, and programming of physical robotic systems. Students experience entire robot creation process, covering conceptual design, detailed design, simulation and modeling, digital manufacturing, electronics and sensor design, and software programming.

MECE E4612x or y Sustainable manufacturing
3 pts. Lect: 3. Professor Yao.
Prerequisite(s): Introductory course in engineering materials and manufacturing processes or instructor's permission. Fundamentals of sustainable design and manufacturing, metrics of sustainability, analytical tools, principles of life cycle assessment, manufacturing tools, processes and systems energy assessment and minimization in manufacturing, sustainable manufacturing automation, sustainable manufacturing systems, remanufacturing, recycling and reuse.

BMME E4702x Advanced musculoskeletal biomechanics
3 pts. Lect: 3. Not offered in 2024–2025.
Advanced analysis and modeling of the musculoskeletal system. Topics include advanced concepts of 3D segmental kinematics, musculoskeletal dynamics, experimental measurements of joints kinematics and anatomy, modeling of muscles and locomotion, multibody joint modeling, introduction to musculoskeletal surgical simulations.

MEBM E4703x Molecular mechanics in biology
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ENME E3105, APMA E2101, or instructor's permission. Mechanical understanding of biological structures including proteins, DNA and RNA in cells and tissues. Force response of proteins and DNA, mechanics of membranes, biophysics of molecular motors, mechanics of protein-protein interactions. Introduction to modeling and simulation techniques, and modern biophysical techniques such as single molecule FRET, optical traps, AFM, and superresolution imaging, for understanding molecular mechanics and dynamics.

MEBM E4710x or y Morphogenesis: shape and structure in biological materials
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Courses in mechanics, thermodynamics, and ordinary differential equations at the undergraduate level or instructor's permission. Introduction to how shape and structure are generated in biological materials using engineering approach emphasizing application of fundamental physical concepts to a diverse set of problems. Mechanisms of pattern formation, self-assembly, and self-organization in biological materials, including intracellular structures, cells, tissues, and developing embryos. Structure, mechanical properties, and dynamic behavior of these materials. Discussion of experimental approaches and modeling. Course uses textbook materials as well as collection of research papers.

MEIE E4810y Introduction to human spaceflight
3 pts. Lect: 3. Professor Massimino.
Prerequisite(s): Department permission and knowledge of MATLAB or equivalent. Introduction to human spaceflight from a systems engineering perspective. Historical and current space programs and spacecraft. Motivation, cost, and rationale for human space exploration. Overview of space environment needed to sustain human life and health, including physiological and psychological concerns in space habitat. Astronaut selection and training processes, spacewalking, robotics, mission operations, and future program directions. Systems integration for successful operation of a spacecraft. Highlights from current events and space research, Space Shuttle, Hubble Space Telescope, and International Space Station (ISS). Includes a design project to assist International Space Station astronauts.

MECE E4811x Aerospace human factors engineering
3 pts. Lect: 2.5. Professor Massimino.
Prerequisite(s): Instructor's permission. Engineering fundamentals and experimental methods of human factors design and evaluation for spacecraft which incorporate human-in-the-loop control. Develop understanding of human factors specific to spacecraft design with human-in-the-loop control. Design of human factors experiments utilizing task analysis and user testing with quantitative evaluation metrics to develop a sate and high-performing operational space system. Human-centered design, functional allocation and automation, human sensory performance in the space environment, task analysis, human factors experimental methods and statistics, space vehicle displays and controls, situation awareness, workload, usability, manual piloting and handling qualities, human error analysis and prevention, and anthropometrics.

MECE E4899x and y Graduate research training
0 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Research training course. Recommended in preparation for laboratory-related research.

MECE E4990x or y Special topics in mechanical engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Permission of the instructor. Topics and Instructors change from year to year. For advanced undergraduate students and graduate students in engineering, physical sciences, and other fields.

MECE E4998x and y M.S. projects in mechanical engineering
1–3 pts. Members of the faculty.
Prerequisite(s): Instructor's permission. Master's level independent project involving theoretical, computational, experimental, or engineering design work. May be repeated, subject to master's program guidelines. Students must submit both a project outline prior to registration and a final project write-up at the end of the semester.

MECE E4999x and y Fieldwork
1 pt. Professor Lipson.
Prerequisite(s): Instructor's written permission. Only for ME graduate students who need relevant off-campus work experience as part of their program of study as determined by the instructor. Written application must be made prior to registration outlining proposed study program. Final reports required. May not be taken for pass/fail credit or audited. International students must consult with the International Students and Scholars Office.

MECE E6100x Advanced mechanics of fluids
3 pts. Lect: 3. Professor Ateshian.
Prerequisite(s): MATH UN2030 and MECE E3100. Eulerian and Lagrangian descriptions of motion. Stress and strain rate tensors, vorticity, integral and differential equations of mass, momentum, and energy conservation. Potential flow.

MECE E6102x or y Computational heat

transfer and fluid flow
3 pts. Lect: 3. Professor Demetriou.
Prerequisite(s): MECE E3100 and E3311. Mathematical description of pertinent physical phenomena. Basics of finite-difference methods of discretization, explicit and implicit schemes, grid sizes, stability, and convergence. Solution of algebraic equations, relaxation. Heat conduction. Incompressible fluid flow, stream function-vorticity formulation. Forced and natural convection. Use of primitive variables, turbulence modeling, and coordinate transformations.

MECE E6103x Compressible flow
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): APMA E4200, MECE E3100 and E3301. Fundamental analysis of compressible flows and its applications for various sonic/supersonic elements including supersonic airfoils/projectiles, nozzles, and shock tubes. Steady and unsteady shock/expansion waves, oblique shock waves. Shock reflections, methods of characteristic.

MECE E6104x Case studies in computational fluid dynamics
3 pts. Lect: 3. Professor Bilson.
Prerequisite(s): APAM E4200 and MECE E6100. Corequisite(s): APAM E4300 and MECE E4400. Hands-on case studies in computational fluid dynamics, including steady and transient flows, heat and mass transfer, turbulence, compressible flow and multiphase flow. Identifying assumptions, computational domain selection, model creation and setup, boundary conditions, choice of convergence criteria, visualization and interpretation of computed results. Taught in the Mechanical Engineering Computer Laboratory with Computational Fluid Dynamics software.

MECE E6105y Transport phenomena in the presence of interfaces
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MECE E3301 Thermodynamics and MECE E3311 Heat transfer; MECE E4100 Mechanics of fluids, or equivalent or instructor’s permission; CHEE E4252 Introduction to surface and colloid chemistry, or the equivalent, or the instructor’s permission. Surface energy and capillary phenomena. Wetting and spreading of liquids, wetting line pinning and hysteresis, dynamics of wetting. Surfactants. Bubbles: nucleation, stability, dynamics, microstreaming. Jets and Drops: generation, dynamics, stability and impact with surfaces. Measurement of transport phenomena involving interfaces. Interfacial transport phenomena involving thermal, chemical or electrical gradients. Applications in microfluidic systems.

MECE E6106x Finite element method for fluid flow and fluid-structure interactions
3 pts. Lect: 3. Professor Vedula.
Prerequisite(s): MECE E4100 or E6100, ENME E4332, or equivalents, or instructor's permission and high-level programming language (Fortran, C, C++, Python, MATLAB, etc). Solving convection-dominated phenomena using finite element method (FEM), including convection-diffusion equation, Navier-Stokes, equation for incompressible viscous flows, and nonlinear fluid-structure interactions (FSI). Foundational concepts of FEM include function spaces, strong and weak forms, Galerkin FEM, isoparametric discretization, stability analysis, and error estimates. Mixed FEM for Stokes flow, incompressibility and inf-sup conditions. Stabilization approaches, including residue-based variational multiscale methods. Arbitrary Lagrangian-Eulerian (ALE) formulation for nonlinear FSI, and selected advanced topics of research interest.

MECE E6137x or y Nanoscale actuation and sensing
3 pts. Lect: 3. Professor Schuck.
Prerequisite(s): PHYS UN1402 or UN1602 or equivalent, or instructor's permission. Interaction of light with nanoscale materials and structures for purpose of inducing movement and detecting small changes in strain, temperature, and chemistry within local environments. Methods for concentrating and manipulating light at length scales below the diffraction limit. Plasmonics and metamaterials, as well as excitons, phonos, and polaritons and their advantages for mechanical and chemical sensing, and controlling displacement at nanometer length scales. Applications to nanophotonic devices and recently published progress in nanomechanics and related fields.

MECE E6200y Turbulence
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MECE E6100. Introductory concepts and statistical description. Kinematics of random velocity fields, dynamics of vorticity, and scalar quantities. Transport processes in a turbulent medium. Turbulent shear flows: deterministic and random structures. Experimental techniques, prediction methods, and simulation.

MEBM E6310x–E6311y Mixture theories for biological tissues, I and II
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MECE E6422 and APMA E4200 or equivalent. Development of governing equations for mixtures with solid matrix, interstitial fluid, and ion constituents. Formulation of constitutive models for biological tissues. Linear and nonlinear models of fibrillar and viscoelastic porous matrices. Solutions to special problems, such as confined and unconfined compression, permeation, indentation and contact, and swelling experiments.

MECE E6313x Advanced heat transfer
3 pts. Lect: 3. Professor Narayanaswamy.
Prerequisite(s): MECE E3311. Corequisite(s): MECE E6100. Application of analytical techniques to the solution of multidimensional steady and transient problems in heat conduction and convection. Lumped, integral, and differential formulations. Topics include use of sources and sinks, laminar/turbulent forced convection, and natural convection in internal and external geometries.

MECE E6320x or y Multiscale phenomena in gases
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): Knowledge of advanced thermodynamics (e.g., MECE E4302), or combustion (e.g., MECH E4320), or instructor's permission. Gaseous phenomena from a molecular to macroscopic perspective. Quantum mechanics, statistical thermodynamics, nonequilibrium statistical mechanics, reaction rate theories, master equation, relaxation processes, kinetic theory, equations of state, transport theories, and kinetic-transport equations. Applications to combustion, aerospace gas dynamics, and high-frequency sound propagation.

MECE E6400y Advanced machine dynamics
3 pts. Lect: 3. Professor Chbat.
Prerequisite(s): MECE E3401. Review of classical dynamics, including Lagrange’s equations. Analysis of dynamic response of high-speed machine elements and systems, including mass-spring systems, cam-follower systems, and gearing; shock isolation; introduction to gyrodynamics.

MECE E6422x–E6423y Introduction to the theory of elasticity, I and II
3 pts. Lect: 3. Professor Myers or Kysar.
Corequisite(s): APMA E4200. Analysis of stress and strain. Formulation of the problem of elastic equilibrium. Torsion and flexure of prismatic bars. Problems in stress concentration, rotating disks, shrink fits, and curved beams; pressure vessels, contact and impact of elastic bodies, thermal stresses, propagation of elastic waves.

MECE E6424x Vibrations in machines, I
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): MECE E3401. Review of vibration analysis of systems and mechanisms with one degree of freedom. Natural frequencies. Forced vibrations. Effects of dry and viscous friction. Energy methods of Rayleigh and Ritz. Suppression and elimination of vibration. Vibration isolation. Measuring instruments. Critical speeds in machinery. Synchronous whirl. Half-frequency whirl. Influence of bearing characteristics on critical speeds. Effect of gyroscopic moments. Systems with multiple degrees of freedom. Dynamic vibration absorbers. Self-tuning absorbers of pendulum and roller types. Lagrangian equations of motion as applied to vibrating systems. General equations for transverse critical speeds of shafts. Surging of helical springs.

MEEM E6432y Small-scale mechanical behavior
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): ENME E3113 or equivalent; APMA E4200 or equivalent. Mechanics of small-scale materials and structures require nonlinear kinematics and/or nonlinear stress vs. strain constitutive relations to predict mechanical behavior. Topics include variational calculus, deformation and vibration of beam, strings, plates, and membranes; fracture, delamination, bulging, buckling of thin films, among others. Thermodynamics of solids will be reviewed to provide the basis for a detailed discussion of nonlinear elastic behavior as well as the study of the equilibrium and stability of surfaces.

EEME E6601x Introduction to control theory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): MATH UN2030. A graduate-level introduction to classical and modern feedback control that does not presume an undergraduate background in control. Scalar and matrix differential equation models and solutions in terms of state transition matrices. Transfer functions and transfer function matrices, block diagram manipulations, closed loop response. Proportional, rate, and integral controllers, and compensators. Design by root locus and frequency response. Controllability and observability. Luenberger observers, pole placement, and linear-quadratic cost controllers.

EEME E6602y Modern control theory
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): EEME E6601 or E4601 or ELEN E6201, or instructor's permission. Singular value decomposition. ARX model and state space model system identification. Recursive least squares filters and Kalman filters. LQR, Hlinear robust control, predictive control, adaptive control. Liapunov and Popov stability. Nonlinear adaptive control, nonlinear robust control, sliding mode control.

EEME E6610y Optimal control theory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): EEME E6601 or E4601 or instructor's permission. Covers topics in calculus of variations, Pontryagin maximum principle, quadratic cost optimal control, predictive control, dynamic programming for optimal control, Kalman filtering, numerical methods for solution. Some applications discussed include minimum energy subway operation (our solution saved 11% in tests on the Flushing Line, and the method was adopted by the transit authority, saving many millions of dollars per year), minimum time robot optimal control allowing one to run assembly lines faster for increased productivity.

MECE E6614x or y Advanced topics in robotics and mechanism synthesis
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): APMA E2101, E3101, MECE E4602 (or COMS W4733). Recommended: MECE E3401 or instructor's permission. Kinematic modeling methods for serial, parallel, redundant, wire-actuated robots and multifingered hands with discussion of open research problems. Introduction to screw theory and line geometry tools for kinematics. Applications of homotopy continuation methods and symbolic-numerical methods for direct kinematics of parallel robots and synthesis of mechanisms. Course uses textbook materials as well as a collection of recent research papers.

MECE E6615x or y Robotic manipulation: sensing, planning, design, and execution
3 pts. Lect: 3. Professor Ciocarlie.
Prerequisite(s): MECE E4602 or COMS W4733. Theory and mechanisms of robotic manipulation, from sensor data, reasoning, and planning to implementation and execution. Grasp quality measures and optimization; planning and execution for manipulation primitives; sensor modalities: vision, touch, and proprioception; simulation for manipulation planning; design of robot manipulators. Grading based on a combination of class presentations of novel research results in the field, participation in discussions, and course projects combining simulation, processing of sensor data, planning for manipulation, design, and implementation on real robot hands.

MECS E6616x or y Robot learning
3 pts. Lect: 3. Professor Ciocarlie.
Prerequisite(s): MECE E4602 or MECS E4603 or COMS W4733. Robots using machine learning to achieve high performance in unscripted situations. Dimensionality reduction, classification, and regression problems in robotics. Deep Learning: Convolutional Neural Networks for robot vision, Recurrent Neural Networks, and sensorimotor robot control using neural networks. Model Predictive Control using learned dynamics models for legged robots and manipulators. Reinforcement Learning in robotics: model-based and model-free methods, deep reinforcement learning, sensorimotor control using reinforcement learning.

MECE E6617y Advanced kinematics, dynamics and control in robotics
3 pts. Lect: 3. Professor Agrawal.
Prerequisite(s): Course on linear and/or nonlinear control theory, Introduction to Robotics, or instructor's permission. Advanced topics in robotics using fundamentals of kinematics, dynamics, and control. Topics include: characterization of orientation and angular velocity of rigid bodies, kinematic solutions of planar mechanisms, dynamics of closed chains and free-floating bodies, gravity balancing of mechanism, dynamics and dependence of inertia redistribution, under-actuation systems, feedback linearization of SISO systems, feedback linearization of MIMO systems, design of under-actuated open-chain robots, parallel-actuated robots.

MECE E6620x or y Applied signal recognition and classification
3 pts. Lect: 3. Professor Beigi.
Prerequisite(s): MATH UN2030, APMA E3101, knowledge of a programming language, or permission of instructor. Applied recognition and classification of signals using a selection of tools borrowed from different disciplines. Applications include human biometrics, imaging, geophysics, machinery, electronics, networking, languages, communications, and finance. Practical algorithms are covered in signal generation, modeling, feature extraction, metrics for comparison and classification, parameter estimation, supervised, unsupervised and hierarchical clustering and learning, optimization, scaling and alignment, signals as codes emitted from natural sources, information, and extremely large-scale search techniques.

MECE E6700x Carbon nanotube science and technology
3 pts. Lect: 3. Professor Schuck.
Prerequisite(s): Knowledge of introductory solid-state physics (e.g., PHYS GU4018, APPH E6081, or MSAE E3103) or instructor's permission. Basic science of solid-state systems. Crystal structure, electronic and phonon band structures of nanotubes. Synthesis of nanotubes and other nanomaterials. Experimental determination of nanotube structures and techniques for nanoscale imaging. Theory and measurement of mechanical, thermal, and electronic properties of nanotubes and nanomaterials. Nanofabrication and nanoelectronic devices. Applications of nanotubes.

MECE E6710y Nanofabrication laboratory
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): ELEN E6945 or instructor's permission. Laboratory in techniques for fabrication at the nanometer scale. Electron-beam lithography. Plasma etching and 3D nanofabrication. Thin film deposition. Self-assembly and "bottom up" nanofabrication. Fabrication of and testing of complete nanodevices. A lab fee of $300 is required.

MECE E6720x Nano/microscale thermal transport process
3 pts. Lect: 3. Not offered in 2024–2025.
Nano- and microscale origins of thermal transport phenomena by molecules, electrons, phonons, and photons. Quantum mechanics and statistical physics. Density of states. Kinetic theory of gases. Boltzmann transport equation (BTE), classical and quantum size effects. Landauer formalism for transport via nanostructures. Macroscopic constitutive equations from BTE. Application to electronics cooling, thermoelectric and thermophotovoltaic devices, and energy conversion.

MECE E8020x or E8021y Master's thesis
3–6 pts. Members of the faculty.
Research in an area of mechanical engineering culminating in a verbal presentation and a written thesis document approved by the thesis adviser. Must obtain permission from a thesis adviser to enroll. Recommended enrollment for two terms, one of which can be the summer. A maximum of 6 points of master's thesis may count toward an M.S. degree, and additional research points cannot be counted. On completion of all master's thesis credits, the thesis adviser will assign a single grade. Students must use a department-recommended format for thesis writing.

MECE E8100y Advanced topics in fluid mechanics
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): MECE E6100. May be taken more than once, since its content has minimal overlap between consecutive years. Selected topics from viscous flow, turbulence, compressible flow, rarefied gas dynamics, computational methods, and dynamical systems theory, non-Newtonian fluids, etc.

MECE E8501y Advanced continuum biomechanics
3 pts. Lect: 2. Professor Myers.
Prerequisite(s): Instructor's permission. The essentials of finite deformation theory of solids and fluids needed to describe mechanical behavior of biological tissue: kinematics of finite deformations, balance laws, principle of material objectivity, theory of constitutive equations, concept of simple solids and simple fluids, approximate constitutive equations, some boundary-value problems. Topics include one- and two-point tensor components with respect to generalized coordinates; finite deformation tensors, such as right and left Cauchy-Green tensors; rate of deformation tensors, such as Rivlin-Ericksen tensors; various forms of objective time derivatives, such as corotational and convected derivatives of tensors; viscometric flows of simple fluids; examples of rate and integral type of constitutive equations.

EEME E8601y Advanced topics in control theory
3 pts. Lect: 3. Not offered in 2024–2025.
Prerequisite(s): 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, system identification, Kalman filtering, etc.

MECE E8990x and y Special topics in mechanical engineering
3 pts. Lect: 3. Instructor to be announced.
Prerequisite(s): Instructor's permission. May be taken for credit more than once. The instructor from the Mechanical Engineering Department and the topics covered will vary from year to year. Intended for students with graduate standing in Mechanical Engineering and other engineering and applied sciences.

MECE E9000x-E9001y and E9002s Graduate research and study
1–3 pts. Members of the faculty.
Theoretical or experimental study or research in graduate areas in mechanical engineering and engineering science.

MECE E9500x and y Graduate seminar
0 pts. Pass/fail only. Professor Schuck.
All doctoral students are required to complete successfully four semesters of the mechanical engineering seminar MECE E9500.

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

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

Undergraduate Minors

TUS · SOPHOCLES · PLATO · ARISTOTLE · DEMOSTHENES · CICERO · VERGIL

UNDERGRADUATE MINORS

Undergraduate minors are designed to allow engineering and applied science students to study, to a limited extent, a discipline other than their major. Besides engineering minors offered by Columbia Engineering departments, liberal arts minors are also available.

A minor requires at least 15 points of credit, and no more than one course can be taken outside of Columbia or met through AP or IB credit. This includes courses taken through study abroad. In Engineering departments with more than one major program, a minor in the second program may be permitted, if approved by the department.

No substitutions or changes of any kind from the approved minors are permitted (see lists below). No appeal for changes will be granted. Please note that the same courses may not be used to satisfy the requirements of more than one minor. No courses taken for pass/fail may be counted for a minor. Minimum GPA for the minor is 2.0. Departments outside the Engineering School have no responsibility for nonengineering minors offered by Engineering.

For a student to receive credit for a course taken while studying abroad, the department offering the minor must approve the course in writing, ahead of the student's study abroad.

Students must expect a course load that is heavier than usual. In addition, unforeseen course scheduling changes, problems, and conflicts may occur. The School cannot guarantee a satisfactory completion of the minor.

MINOR IN ANTHROPOLOGY

1. ANTH UN1002: The interpretation of culture (3
or ANTH UN1008: The rise of civilization (3)

Note: UN1002 serves as a preview to sociocultural anthropology, while UN1008 serves as a preview to archaeology.

2–5. Any four courses in the Anthropology department, in ethnomusicology, or taught by an Anthropology instructor, regardless of department. No distribution requirement.

MINOR IN APPLIED MATHEMATICS

Prospective students should consult the first- and second-year requirements for applied mathematics majors to ensure that prerequisites for the applied mathematics minor are satisfied in the first two years.

Coursework counting toward the applied mathematics minor may not include advanced placement credits. Any substitutions for the courses listed below require the approval of the applied mathematics program adviser.

1. APMA E3101: Linear algebra (3)
or COMS W3251: Comp. linear algebra (3)
or MATH UN2010: Linear algebra (3)

2. APMA E3102: Partial differential equations (3)
or MATH UN3028: Partial differential equations (3)

3–5. Three of the following courses:
APMA E4300: Intro to numerical methods (3)
APMA E4204: Func of complex variable (3)
APMA E4101: Intro to dynamical systems (3)
MATH UN2500: Analysis and optimization (3)
STAT GU4203: Probability theory (3)
STAT GR4204: Statistical inference (3)
or any other course designated *APMA, MATH, STAT, IEOR,* or *COMS* that is approved by the applied mathematics program adviser.

MINOR IN APPLIED PHYSICS

Prospective students should consult the first- and second-year requirements for applied physics majors to ensure that prerequisites for the applied physics minor are satisfied in the first two years.

Coursework counting toward the applied physics minor may not include advanced placement credits.

1. APPH E4901: Problems in applied physics (1)

2. APPH E3200: Mechanics (3)

3. APPH E3100: Intro to quantum mechanics (3)

4. APPH E3300: Applied electromagnetism (3)

5. MSAE E3111: Thermodynamics, kinetic theory, and statistical mechanics (3)

6. Two of the following courses
APPH E4010: Intro to nuclear science (3)
APPH E4100: Quantum physics of matter (3)
APPH E4110: Modern optics (3)
APPH E4112: Laser physics (3)
APPH E4300: Applied electrodynamics (3)
APPH E4301: Intro to plasma physics (3)

MINOR IN ARCHITECTURE

1. Studio: One to three of the following courses:
ARCH UN1020: Intro to architectural design and visual culture (3)
ARCH UN2101: Architectural design: systems and materials (4)
ARCH UN2103: Architectural design: environments and mediations (4)

2. ARCH UN3117: Modern architecture in the world (3)

3–5. Lecture, Seminars, and Workshop: One to three courses: any lecture, seminar,

or workshop offered or approved by the Architecture Department

MINOR IN ART HISTORY

1–3. At least one course in three of four of the historical periods: (a) Ancient (up to 400 CE/AD); (b) 400–1400; (c) 1400–1700; (d) 1700–present

4–5. Two additional courses covering two of five world regions: (a) Africa; (b) Asia; (c) Europe; (d) North America; (e) Australia; (f) Latin America; (g) Middle East; (h) medieval Europe

6–7. Two courses from the Department of Art History and Archaeology

MINOR IN BIOMEDICAL ENGINEERING

The Biomedical Engineering program offers a minor that consists of the following six courses. Participation in the minor is subject to the approval of the major program adviser.

1. BIOL UN2005: Introduction to biology, I (3)

2. BIOL UN2006: Introduction to biology, II (3)

3. BMEN E3010: Biomedical engineering, I (3)

4. BMEN E3020: Biomedical engineering, II (3)

5. BMEN E4001: Quantitative physiology, I (3)

6. BMEN E4002: Quantitative physiology, II (3)

MINOR IN CHEMICAL ENGINEERING

Of the six courses required, at least three must have the *CHEN*, *CHEE,* or *CHAP* designator:

1. CHEN E2100: Intro to chemical engineering (3)

2. CHEE E3010: Prin of chemical engineering thermodynamics (3)
or MSAE E3111: Thermodynamics, kinetic theory, and statistical mechanics (3)
or MECE E3301: Thermodynamics (3)
or BMEN E4210: Thermodynamics of biological systems (3)

3. CHEN E3110: Transport phenomena, I (3)
or EAEE E3200: Applied transport and chemical rate phenomena (3)
or MECE E3100: Intro to mech of fluids (3)
or ENME E3161: Fluid mechanics (4)
or BMEN E3220: Fluid biomechanics (4)

4. CHEN E4230: Reaction kinetics and reactor design (3)

5–6. Two of the following courses:
Any 3000-level or higher *CHEN or cross-listed (CHAP, BMCH, CHEE, CHBM, CHOR, MECH)* course

MINOR IN CIVIL ENGINEERING

1. CIEN E3121: Structural analysis (3)
or ENME E3161: Fluid mechanics (4)
or MECE E3100: Intro to mech of fluids (3)

2. ENME E3105: Mechanics (4)

3. ENME E3113: Mechanics of solids (3)

4–6. Electives: Three of the following courses:
CIEN E3000: The art of structural design (3)
ENME E3161: Fluid mechanics (4)
ENME E3114: Exp mechanics of materials (4)
ENME E3332: A first course in finite elements (3)
MECE E3414: Adv strength of materials (3)
CIEN E3125: Structural design (3)
CIEN E4241: Geotech eng fundamentals (3)
EACE E3250: Hydrosystems engineering (3)
EACE E4163: Sustainable water treat/reuse (3)
CIEN E3129: Project mgmt for construction (3)
CIEN E4131: Prin of construction tech (3)

MINOR IN COMPUTER SCIENCE

Students who pass the Computer Science Advanced Placement Exam A with a 4 or 5 will receive 3 points and exemption from *COMS W1004*. Participation in the minor is subject to the approval of the major program adviser. For further information, please see the Quick Guide at cs.columbia.edu/education/undergraduate.

The Computer Science Minor consists of 6 courses as follows:

1. COMS W1004: Intro to computer science and programming in Java (3)

or COMS W1007: Honors intro to comp sci (3)

2. COMS W3134: Data structures in Java (3)
or COMS W3137: Honors data structures and algorithms (4)

3. COMS W3203: Discrete mathematics (4)

4. One course of the following:
COMS W3157: Advanced programming (3)
COMS W3261: Comp science theory (3)

CSEE W3827: Fund of computer systems (3)

5. Any 3000-level or 4000-level COMS/CSXX/XXCS course of at least 3 points

6.Any 3000-level or 4000-level COMS/CSXX/XXCS course of at least 3 points OR one course from the following (linear algebra or probability/statistics): APMA E3101, APMA E2101, MATH UN2010, MATH UN2015, IEOR E3658, STAT UN1201, or STAT GU4001.

MINOR IN DANCE

The dance minor consists of five 3-point courses. Please note that no performance/choreography courses below count toward the nontech requirement for Engineering students.

1–2. History/criticism: Two of the following:
DNCE BC2565: World dance history (3)
DNCE BC2570: Dance in New York City (3)
DNCE BC3000: From the page to the dance stage (3)
DNCE BC3001: Western theatrical dance from the Renaissance to the 1960s (3)
DNCE BC3002: Choreographing race (3)
DNCE BC3200: Dance in film (3)
DNCE BC3240: Seeing the body (3)
DNCE BC3550: Dance in Africa (3)
DNCE BC3567: Dance of India (3)
DNCE BC3576: Dance criticism (3)
DNCE BC3577: Performing the political (3)

3–4. Performance/choreography: Two of the following:
DNCE BC2563: Dance composition: form (3)
DNCE BC2564: Dance composition: content (3)
DNCE BC2567: Music for dance (3)
DNCE BC3601-3607: Rehearsal and performance in dance (1–3)

5. One elective

MINOR IN EARTH AND ENVIRONMENTAL ENGINEERING

1–3. Three of the following courses:
EAEE E3103: Energy, minerals, and mat syst (3)
CIEE E3255: Environmental control and pollution reduction systems (3)
EAEE E4001: Industrial ecology of earth res (3)
EAEE E4003: Intro to aquatic chemistry (3)
EAEE E4004: Physical processing and recovery of solids (3)
EAEE E4006: Field methods for environ eng (3)
EAEE E4009: GIS for resource, environment, and infrastructure management (3)
EAEE E4150: Air pollution prevention and control (3)
EAEE E4160: Solids and hazardous waste management (3)
EAEE E4200: Introduction to sustainable production of earth mineral & metal resources (3)
EAEE E4257: Environ data analysis and modeling (3)
EAEE E4361: Econ of earth res industries (3)
EACH E4560: Particle technology (3)

4–6. Three of the following courses:
CHEE E3010: Prin of chemical engineering thermodynamics (3)
CHEE E3110: Transport phenomena, I (3)
CIEN E3141: Soil mechanics (3)
CIEE E3250: Hydrosystems engineering (3)
ECIA W4100: Mgmt and dev of water systems (3)
CIEE E4163: Environ eng: wastewater (3)
EAEE E4190: Photovoltaic systems eng (3)
MECE E4211: Energy: sources and conv (3)
CIEN E4250: Waste contain design and prac (3)
CHEE E4252: Intro to surface and colloid chem (3)

CIEE E4252: Environmental engineering (3)
CIEE E4257: Groundwater contaminant transport and remediation (3)
CHEN E4410: Environmental control technology (3)

MINOR IN EAST ASIAN STUDIES

1–5. Any two of the survey courses on Chinese, Japanese, Korean, Tibetan, or Vietnamese civilization (ASCE UN1359, UN1361, UN1363, UN1365, UN1367), plus three elective courses dealing with East Asia

Note: The elective courses may be taken in departments outside of East Asian Languages and Cultures. The minor does not include a language requirement. However, one semester of an East Asian language class may be used to fulfill one of the three electives, as long as at least two semesters of that language have been taken. Placement exams may not be used in place of these courses.

MINOR IN ECONOMICS

1. ECON UN1105: Principles of economics (4)

2. ECON UN3211: Intermediate microeconomics (4)

3. ECON UN3213: Intermediate macroeconomics (4)

4. ECON UN3412: Introduction to econometrics (4)

Note: UN1105 is a prerequisite for *UN3211, UN3213,* and *UN3412.* Students must have completed Calculus I before taking *UN3213,* Calculus III before taking *UN3211,* and one of the introductory statistics courses (see list) before taking *UN3412.*

5–6. Electives: Two of the following courses:
ECON UN2105: American economy (3)
ECON UN2257: Global economy (3)
ECON UN3025: Financial economics (3)
ECON UN3265: Econ of money and banking (3)
ECON UN3901: Economics of education (3)
ECON UN3952: Macro and formation of expectations (3)
ECON GU4020: Econ of uncertainty and info (3)
ECON GU4211: Advanced microeconomics (3)
ECON GU4213: Advanced macroeconomics (3)
ECON GU4230: Economics of NYC (3)
ECON GU4251: Industrial organization (3)
ECON GU4260: Market design (3)
ECON GU4280: Corporate finance (3)
ECON GU4301: Economic growth and development (3)
ECON GU4321: Economic development (3)
ECON GU4370: Political economy (3)
ECON GU4400: Labor economics (3)
ECON GU4412: Advanced econometrics (3)
ECON GU4413: Economics of time series and forecasting (3)
ECON GU4415: Game theory (3)
ECON GU4438: Economics of race in the U.S. (3)
ECON GU4465: Public economics (3)
ECON GU4480: Gender and applied economics (3)
ECON GU4500: International trade (3)
ECON GU4505: International macro (3)
ECON GU4700: Financial crises (3)
ECON GU4710: Finance and the real economy (3)
ECON GU4750: Globalization and its risks (3)
ECON GU4840: Behavioral economics (3)
ECON GU4850: Cognitive mechanisms and economic behavior (4)
ECON GU4860: Behavioral finance (3)

Note: Electives may be taken only after the completion of both *UN3211* and *UN3213,* with the exception of *UN2257 and UN2105,* which may be taken after completion of *UN1105.* Some of the elective courses listed above have additional prerequisites. Courses may be taken only after the completion of all prerequisites. Please see the Columbia College bulletin for course descriptions and complete lists of prerequisites.

7. Statistics: One of the following three probability and statistics options (course or sequence):
  a. SIEO W3600 (or STAT GU4001): Intro to probability and statistics
  b. IEOR E3658: Probability **and E4307:** Applied statistical models
  c. STAT UN4203 (or GR5203): Intro to probability and statistics **and STAT UN4204 (or GR5204):** Statistical inference

Notes:

- The statistics course must be finished before taking *UN3412,* and it is recommended that students take *UN3412* in the semester following the statistics course.
- Some courses done as part of the economics minor may count toward fulfilling the School's nontechnical requirements. However, other courses, such as *UN3412: Intro to econometrics,* may not be applied toward satisfaction of the nontechnical course requirements. To determine which economics class can count toward the nontech elective requirement, please consult the nontech elective section of this bulletin for further details.
- Students with AP credit for economics and an exemption for *UN1105* may use the credit toward the minor.
- Transfer or study abroad credits may not be applied to fulfill the requirements of the economics minor.

MINOR IN ELECTRICAL ENGINEERING

1. ELEN E1201: Intro to electrical eng (3.5)
(May be replaced by a similar course or roughly equivalent experience)

2. ELEN E3201: Circuit analysis (3.5)

3. CSEE W3827: Fund of computer systems (3)

4. ELEN E3081 and ELEN E3082: Electrical engineering labs (2)

5. ELEN E3801: Signals and systems (3.5)

6. ELEN E3106: Solid-state dev and mat (3.5)
or ELEN E3401: Electromagnetics (4)

Note: Not available to computer engineering majors

MINOR IN ENGINEERING MECHANICS

1. ENME E3105: Mechanics (4)

2. ENME E3113: Mechanics of solids (3)

3. ENME E3161: Fluid mechanics (4)
or MECE E3100: Intro to mech of fluids (3)

4–6. Electives: Three of the following:
ENME E3106: Dynamics and vibrations (3)
ENME E3114: Exp mechanics of materials (4)
or MECE E3414: Adv strength of materials (3)
CIEN E3121: Structural analysis (3)
ENME E4202: Advanced mechanics (3)
ENME E4113: Advanced mechanics of solids (3)
ENME E4114: Mech of fracture and fatigue (3)
ENME E4214: Theory of plates and shells (3)
ENME E4215: Theory of vibrations (3)
MECE E3301: Thermodynamics (3)

MINOR IN ENGLISH AND COMPARATIVE LITERATURE

1–5. Any five courses in the English Department with no distribution requirement. No speech courses, only one writing course and excluding ENGL CC1010, may be taken; total 15 points.

MINOR IN ENTREPRENEURSHIP AND INNOVATION

Minimum: 15 points

1–2. Required courses:
IEOR E2261: Accounting and finance (3)
and IEOR E4998: Managing technological innovation and entrepreneurship (3)

3–5. Electives: Three of the following courses:
BIOT GU4180: Entrepreneurship in biotech (3)
BUSI W3021: Marketing management (3)
CHEN E4020: Protection of industrial and intellectual property (3)
CIEN E4136: Global entrepreneurship in civil engineering (3)
COMS W4444: Program and problem solving (3)

COMS W4460: Principles of innovation in biotechnology (3)
ECON GU4280: Corporate finance (3)
IEOR E4003: Corporate finance for engineers (3)
IEOR E4510: Project management (3)
IEOR E4550: Entrepreneurial business creation for engineers (3)
IEOR E4560: Lean launchpad (3)
(by application only with adviser approval)

MINOR IN ETHNICITY AND RACE

1. The following course:
CSER UN1010: Introduction to comparative ethnic studies (3)

2. One of the following courses:
CSER UN3928: Colonization/decolonization (3)
CSER UN3942: Race and racisms (3)

3–5. Three additional CSER courses with approval from the Department

MINOR IN FILM AND MEDIA STUDIES

1. FILM UN1000: Introduction to film and media studies (3)

2. History courses: one of the following:
FILM UN2010: Cinema history 1: Beginning–1930 (3)
FILM UN2020: Cinema History 2: 1930–60 (3)
FILM UN2030: Cinema History 3: 1960–90 (3)
FILM UN2040: Cinema History 4: after 1990 (3)
3–5. Any three courses offered by the Department of Film and Media Studies excluding laboratory courses

MINOR IN FRENCH AND FRANCOPHONE STUDIES

15 points beyond second-year French

1–2. FREN UN3409 and UN3410: Intro to French and francophone history and Intro to French and francophone literature (3, 3)

3–5. Three additional courses in French beyond satisfaction of the language requirement

MINOR IN GERMAN

15 points beyond second-year German

1. GERM UN3001 or 3002: Adv German, I or II (3)

2. GERM UN3333: Intro to German literature (3)

3. One of the period survey courses in German literature and culture, GERM UN3442, UN3443, UN3444, UN3445

4–5. Two courses taken from any 3000/4000-level German or CompLit-German courses taught in German or English

MINOR IN GREEK OR LATIN

1–4. A minimum of 13 points in the chosen language at the 1200 level or higher

5. 3 points in ancient history of the appropriate civilization

MINOR IN HISPANIC STUDIES

1. SPAN UN3300: Adv language through content (3) (3)

2–3. SPAN UN3349 and UN3350: Hispanic cultures, I and II (3, 3)

4–5. One additional 3000-level elective course in the Department of Latin American and Iberian Cultures

Note: Please see the director of undergraduate studies in the Department of Latin American and Iberian Cultures for more information and to declare the minor.

MINOR IN HISTORY

1–5. Minimum 5 courses in the History Department with no distribution or seminar requirements. Transfer or study-abroad credits may not be applied.

MINOR IN INDUSTRIAL ENGINEERING

1. IEOR E3658: Probability for engineers (4)
or STAT GU4001: Intro to probability and statistics (3)

2. IEOR E3608: Foundations of optimization (3)

3. IEOR E3402: Production inventory planning and control (4)

4. IEOR E4003: Corporate finance for engineers (3)

5–6. Electives: Two IEOR courses of interest and approved by a faculty adviser[1]

Note: In addition to the required courses, students majoring in operations research and its concentrations (EMS, FE, or Analytics) minoring in industrial engineering must take three industrial engineering courses that are not used to satisfy the requirements of their major.

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[1] Electives should be 3000-level or higher.

MINOR IN LINGUISTICS

1–3. Three of the following courses:
AMST UN3931: Topics in American Studies (languages of America/language contact) (3)
ENGL GU4901: History of the English language (3)
LING UN3101: Introduction to linguistics (3)
LING UN3102: Endangered languages in the global city (3)
LING UN3103: Language, brain, and mind (3)
LING GU4108: Language history (3)
LING GU4120: Language documentation and field methods (3)
LING GU4171: Languages of Africa (3)
LING GU4190: Discourse and pragmatics (3)
LING GU4376: Phonetics and phonology (3)
LING GU4800: Language and society (3)
LING GU4903: Syntax (3)

4–6. Three additional courses from either a) the core linguistics courses, or b) a linguistics-related course from another department subject to approval from the program. Courses previously approved include those listed below:

Anthropology:
ANTH UN1009: Introduction to language and culture (3)
ANTH GU4042: Agent, person, subject, self (3)
ANTH GR6067: Language and its limits (3)
ANTH GR6125: Language, culture, and power (3)

Chinese:
CHNS GU4019: History of Chinese language (3)

Computer Science:
COMS W4705: Natural language processing (3)
COMS W4995: Topics in computer science (with approval) (3)
COMS E6998: Topics in computer science (with approval) (3)

Comparative language and society:
CLPS GU4111: World philology (3)

French:
FREN BC3011: History of the French language (3)

Hungarian:
HUNG UN3343: Descriptive grammar of Hungarian (3)

Philosophy:
PHIL UN2685: Introduction to philosophy of language (3)
PHIL UN3411: Symbolic logic (3)
PHIL UN3685: Philosophy of language (3)
PHIL GU4490: Language and mind (3)

Psychology:
PSYC UN2215: Cognition and the brain (3)
PSYC UN2440: Language and the brain (3)
PSYC UN2450: Behavioral neuroscience (3)
PSYC BC3164: Perception and language (3)
PSYC UN3265: Auditory perception (seminar) (3)
PSYC BC3369: Language development (3)
PSYC GU4232: Production and perception of language (3)
PSYC GU4272: Advanced seminar in language development (3)

Sociology:
SOCI GU4030: Sociology of language (3)

Spanish:
SPAN BC3382: Languages in contact: sociolinguistic aspects of U.S. Spanish (3)
SPAN GU4010: Language crossing in Latinx Caribbean culture production (3)
SPAN GU4030: Spanish pragmatics (3)
SPAN GR5450: A cognitive linguistics account of language (3)

MINOR IN MATERIALS SCIENCE

1–5. Any five MSAE E3000 or MSAE E4000-level courses, excluding MSAE E3900 (Undergraduate research), and excluding MSAE E3156, E3157 (Design project), and excluding MSAE E4301 (Materials science laboratory)

MINOR IN MECHANICAL ENGINEERING

1–4. Four of the following courses:
- **MECE E3100:** Intro to mechanics of fluids (3)
- **or ENME E3161:** Fluid mechanics (4)
- **or CHEN E3110:** Transport phenomena, I (3)
- **or EAEE E3200:** App transport and chemical rate phenomena (3)
- **ENME E3105:** Mechanics (4)
- **ENME E3106:** Dynamics and vibrations (3)
- **MECE E3301:** Thermodynamics (3)
- **or CHEE E3010:** Principles of chemical engineering thermodynamics (3)
- **or MSAE E3111:** Thermodynamics, kinetic theory, and statistical mechanics (3)
- **MECE 3414:** Mechanics of solids for mechanical engineers (3)
- **MECE E3408:** Comp graphics and design (3)
- **MECE E3311:** Heat transfer (3)
- **MECE E3610:** Materials and processes in manufacturing (3)
- **EEME E3601:** Classical control systems (3)

5–6. Electives: Two additional mechanical engineering courses from either the above list or the following (not all courses in this list are given every year):
- **MECE E3401:** Mechanics of machines (3)
- **MECE E3450:** Computer-aided design (3)
- **Any 3-credit 4000-level courses listed in the Mechanical Engineering Bulletin can also be used to fulfill these additional course requirements**

MINOR IN MIDDLE EASTERN, SOUTH ASIAN, AND AFRICAN STUDIES

1–5. Five courses, to be chosen with the approval of the MESAAS Director of Undergraduate Studies; no elementary or intermediate language courses may be counted.

MINOR IN MUSIC

Requires a minimum of 15 credits

1. One of the following courses:
- **MUSI UN3400:** Topics in music and society (3)
- **MUSI UN3128:** History of Western music I (3)
- **MUSI UN3129:** History of Western music II (3)

2. One of the following courses:
- **MUSI UN2318:** Music theory I (3)
- **MUSI UN2319:** Music theory II (3)
- **or** one course at the Computer Music Center

3. Three other nontechnical electives in music*

**Note: music instruction and performance courses may not count toward the 27-credit nontechnical requirement within the 128 credits for the B.S.*

MINOR IN OPERATIONS RESEARCH

- **1. IEOR E3658:** Probability for engineers (4)
  - **or STAT GU4001:** Intro to probability and statistics (3)
- **2. IEOR E3106:** Stochastic systems and applications (3)
  - **or IEOR E4106:** Stochastic models (3)
- **3. IEOR E3608:** Foundations of optimization (4)
- **4. IEOR E3404:** Simulation modeling and analysis (4)
  - **or IEOR E4404:** Simulation (3)

5–6. Electives: Two IEOR courses (6 pts) of interest and approved by a faculty adviser.[1] IEOR E3402: Production-inventory planning and control (3) is strongly recommended

Note: In addition to the required courses, students majoring in industrial engineering must take three operations research courses that are not used to satisfy the requirements of their major.

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[1] Electives should be 3000-level or higher.

MINOR IN PHILOSOPHY

1–5. Any five courses in the Philosophy Department with no distribution requirement; total 15 points. See also the list of exceptions under Elective Nontechnical Courses.

Note: Please be aware that some philosophy courses may not count as nontechnical electives.

MINOR IN POLITICAL SCIENCE

1–2. Two of the following courses:
- **POLS UN1101:** Intro to political theory (3)
- **POLS UN1201:** Intro to American govt and politics (3)
- **POLS UN1501:** Intro to comparative politics (3)
- **POLS UN1601:** International politics (3)

3–5. Any three courses in the Political Science Department with no distribution requirement; total 9 points

MINOR IN PSYCHOLOGY

1. PSYC UN1001: The science of psychology (3)

2–5. Any four courses from, at a minimum, two of the three groups below:

I. PERCEPTION AND COGNITION
Courses numbered in the 2200s, 3200s, or 4200s

II. PSYCHOBIOLOGY AND NEUROSCIENCE
PSYC UN2430: Cognitive neuroscience (3)
Courses numbered in the 2400s, 3400s, or 4400s

III. SOCIAL, PERSONALITY, AND ABNORMAL
Courses numbered in the 2600s, 3600s, or 4600s

MINOR IN RELIGION

1–5. Five courses (total 15 points), one of which must be at the 2000 level

MINOR IN SOCIOLOGY

- **1. SOCI UN1000:** The social world (3)
- **2. SOCI UN3000:** Social theory (3)
- **3–5. Any three 2000-, 3000-, or 4000-level courses offered by the Department of Sociology; total 6 points**

MINOR IN STATISTICS

- **1. STAT UN1101:** Intro to statistics (w/o calculus) (3)
- **2. STAT UN2102:** App statistical computing (3)
- **3. STAT UN2103:** App linear regression analysis (3)
- **4. STAT UN2104:** App categorical data analysis (3)
- **5. STAT UN3105:** Appl. 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 *UN4203, UN4204, UN4205, UN4206,* and *UN4207.*
- 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 E2002:** Alternative energy sources (3)
- **EAEE E2100:** Better planet by design (3)
- **CIEE E3250:** Hydrosystems engineering (3)
- **CIEE E3260:** Eng for comm dev (3)
- **EAEE E3901:** Environmental microbiology (3)

EAEE E4001: Industrial ecology	(3)
ECIA W4100: Mgmt and dev of water systems	(3)
APPH E4130: Physics of solar energy	(3)
EAEE E4190: Photovoltaic systems eng and sustainability	(3)
MECE E4211: Energy sources and conversion	(3)
MECE E4312: Solar thermal engineering	(3)
EAEE E4257: Environmental data analysis	(3)
MECE E4314: Dynamics of green buildings	(3)
EESC GU4404: Regional climate and climate impacts	(3)

5. One of the following courses:

ECON UN2257: Global economy	(3)
PLAN A4151: Found of urban economic analysis	(3)
PLAN A4304: Intro to housing	(3)
ECON UN4321: Economic development	(3)
ECON GU4527: Econ org and develop of China	(3)
PLAN A4579: Intro to environmental planning	(3)
ECON GU4625: Economics of the environment	(3)

6. One of the following courses:

POLS UN3212: Environmental politics	(3)
POLS UN3213: American urban politics	(3)
SOCI UN3235: Social movements	(3)
SOCI UN3324: Global urbanism	(3)

Note: If courses in Group 5 or 6 are not available, requesting approval for a similar course from the groups "Economics" or "Law, Policy and Human Rights," respectively from the Columbia College Sustainable Development course list is possible. For more information visit bulletin.columbia.edu/columbia-college/departments-instruction/sustainable-development/#coursestext.

Interdisciplinary Courses and Professional Development and Leadership Program

INTERDISCIPLINARY ENGINEERING COURSES

Of the following courses, some may be requirements for degree programs, and others may be taken as electives. See your departmental program of study or consult with an adviser for more information.

ENGI E1102x and y The art of engineering
4 pts. Lect: 4. Professor Vallancourt.
Core requirement for all entering SEAS students. A bridge between the science-oriented, high school way of thinking and the engineering point of view. Fundamental concepts of math and science are reviewed and reframed in an engineering context, with numerous examples of each concept drawn from all disciplines of engineering represented at Columbia. Nontechnical issues of importance in professional engineering practice such as ethics, engineering project management, and societal impact are addressed. Lab fee: $350.

ENGI W4100y Research to revenue
3 pts. Lect: 3. Professors Sia and Toubia.
An interschool 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 model 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.

ENGI E4200x Global Engineering
3 pts. Lect 3. Professor Bourtsalas.
Prerequisite(s): Students must be enrolled in the Global Engineering Track (GET) elective specialization. Introduces students to contemporary cases in engineering that impact the world globally and locally. Taught by Columbia Engineering faculty members, approaching cases in an interdisciplinary manner, brings students together from across the MS programs. Focuses on the School's vision of Engineering for Humanity in five areas: Sustainability, Health, Security, Connectedness, and Creativity.

ENGI E4201s Global engineering fieldwork
1 pt. Lect: 1.
Prerequisite(s): Students must be enrolled in the Global Engineering Track (GET) elective specialization. Instructor's written approval. Final reports required. May not be audited. International students must consult with the International Students and Scholars Office.

ENGI E4250s Summer@SEAS Research Program
0 pt. Lect: 0.
Columbia Engineering's summer on-campus research program for Undergraduate and Master's students. Additional enrichment opportunities comprised of academic and professional seminars, a weekly luncheon, and social programming

ENGI E4300x Design justice: human-centered design and social justice
3 pts. Professors Chilton, Patton, and West.
Prerequisite(s): IEME E4200 or COMS W4170 or instructor's permission. Introduction to Human-Centered Design and Innovation. Unpack the role of design in the market economy for an individual consumer, for a designer/developer, and for an enterprise or other organization. Consider how designing in good faith for most can lead to injustice for some. Examine how to use the PROP framework of the Columbia School of Social Work—power, race, oppression, and privilege can be executed through the design process. Equip students with tools to engage in the design process and to facilitate the engagement of others. Explore strategies for guiding design and innovation toward more just solutions.

ENGI E4990x and y Advanced master's research
1–6 pts.
Prerequisite(s): Previous research at Columbia. program. Research Course for Master's Students. Students must be nominated by a faculty member. The research credits may not be counted towards the credits required for the Master's degree.

ENGI E8000x, y, and s Doctoral fieldwork
1 pts.
Fieldwork is integral to the academic preparation and professional development of doctoral students. This course provides the academic framework for fieldwork experience required for the student's program of study. Fieldwork documentation and faculty adviser approval is required prior to registration. A final written report must be submitted. This course will count toward the degree program and cannot be taken for pass/fail credit or audited. With approval from the department chair or the doctoral program director, doctoral students can register for this course at most twice. In rare situations, exceptions may be granted by the Dean's Office to register for the course more than twice (e.g., doctoral students funded by industrial grants who wish to perform doctoral fieldwork for their corporate sponsor). The doctoral student must be registered for this course during the same term as the fieldwork experience.

For information on courses in other divisions of the University, please consult the bulletins of Columbia College and the Graduate School of Arts and Sciences.

PROFESSIONAL DEVELOPMENT AND LEADERSHIP

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

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

PROFESSIONAL DEVELOPMENT AND LEADERSHIP STAFF

Kaitlynn Liriano
April Neal
Jenny Mak
Elizabeth Strauss
seas-pdl@columbia.edu
pdl.engineering.columbia.edu

PROFESSIONAL DEVELOPMENT AND LEADERSHIP CORE FACULTY

Chuck Garcia: Communication
Helio Fred Garcia: Ethics and Integrity
Sophia Hyoseon Lee: English Communication
Jenny Mak: Resume
Elizabeth Strauss: Business Writing

PROFESSIONAL DEVELOPMENT AND LEADERSHIP COURSES

M.S. Course

ENGI E4000x and y Professional development and leadership for engineers and applied scientists
0 pts. The PDL Instructional Team.
The PDL course aims to enhance and expand Columbia Engineering graduate students' interpersonal, professional, and leadership skills, through five core sessions, covering (1) in-person communication skills; (2) resume; (3) business writing; (4) social media and the job search; and (5) academic and professional ethics and integrity. ENGI E4000 also requires 5 elective sessions to further students' development based on their personal interests. Students must select at least one life management elective and one interview elective. This course is offered at the Pass/D/Fail grading option.

Doctoral Courses

ENGI E6001x and y Professional development and leadership for first year doctoral students
0 pts. The PDL Instructional Team.
For first year doctoral students, emphasizing the skills needed for success in orienting them to Columbia and doctoral studies, including teaching and presentation skills (i.e., Microteaching, how to grade, hold office hours, conduct recitations, etc.); cultivating relationships with mentors, faculty, and colleagues; inclusivity; managing your budget; wellness; research and academic integrity and ethics.

E6002x and y Professional development and leadership for second year doctoral students
0 pts. The PDL Instructional Team.
For second year doctoral students, emphasizing the skills needed for continued success in the doctoral program, including presentation and communication skills; academic writing skills; academic conference preparation; resiliency and project management skills.

E6003x and y Professional development and leadership for third year doctoral students
0 pts. The PDL Instructional Team.
For third year doctoral students to facilitate career exploration including teaching, presentation and communication skills; public speaking and facilitation; CV and resume writing; and Getting Things Done.

E6004x and y Professional development and leadership for doctoral students: fourth year
0 pts. The PDL Instructional Team.
For fourth year doctoral students to facilitate career exploration including teaching, presentation and communication skills; public speaking and facilitation; CV and resume writing; and Getting Things Done.

GRADUATE CAREER PLACEMENT

Austin Cartagena, Assistant Director
Ryan Day, Associate Director
Jackie Tang, Career Placement & PDL Officer
seas-gcp@columbia.edu
careers.engineering.columbia.edu

While enrolled in a graduate program at Columbia Engineering you will also be coached by your dedicated Career Placement Officer. We look forward to working with you on your professional development and job search throughout your time at Columbia.

Applied Mathematics – *Emily McCormack*

Applied Physics – *Emily McCormack*

Biomedical Engineering – *Jacqueline Kishel*

Business Analytics – *Lucy Mahbub (interim)*

Carbon Management – *Raina Ranaghan*

Chemical Engineering – *Raina Ranaghan*

Civil Engineering and Engineering Mechanics – *Emily McCormack*

Computer Engineering – *Jennifer Lee*

Computer Science – *Stephon Moulterie*

Data Science – *Austin Cartagena, Jackie Tang*

Earth and Environmental Engineering – *Raina Ranaghan*

Electrical Engineering – *Jennifer Lee, Jackie Tang*

Executive Masters in Engineering and Applied Science – *Austin Cartagena*

Financial Engineering – *David Fitzgerald*

Industrial Engineering – *Sara Yllescas*

Management Science and Engineering – *Sara Yllescas*

Materials Science – *Emily McCormack*

Medical Physics – *Emily McCormack*

Mechanical Engineering – *Hannah Hyat*

Operations Research – *Cindy Mejia*

ENGLISH COMMUNICATION COURSES

M.S. Courses

ENGI E5000x, y, and s Workplace communication in English
E5001x, y, and s Professional presentation
E5002x, y, and s Professional communication in English
E5003x, y, and s Academic writing
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.

Doctoral Courses

ENGI E7000x, y, and s English communication
E7001x, y, and s Professional presentation
E7002x, y, and s Advanced academic writing
E7009x, y, and s English communication independent studies
0 pts. Lect: 1.7. Professor Lee.
English communication proficiency is important for academic achievement and career success. In small group settings, interactions with instructor and fellow students to improve communication and writing skills. Individual tutoring sessions offered. Note: open only to Columbia Engineering Ph.D. and M.S. to Ph.D.-track students. Grading is Pass/D/Fail.

University and School Policies, Procedures, and Regulations

REGISTRATION AND ENROLLMENT

Registration is the process that reserves seats in particular classes for eligible students. It is accomplished by following the procedures announced in advance of each term's registration period.

Enrollment is the completion of the registration process and affords the full rights and privileges of student status. Enrollment is accomplished by the payment or other satisfaction of tuition and fees and by the satisfaction of other obligations to the University.

Registration alone does not guarantee enrollment nor does registration alone guarantee the right to participate in class. In some cases, students will need to obtain the approval of the instructor, or of a representative of the department that offers a course, or permission of the School offering the class. Students should check this bulletin, their registration instructions, the Directory of Classes, and also with an adviser for all approvals that may be required.

To comply with current and anticipated Internal Revenue Service mandates, the University requires all students who will be receiving financial aid or payment through the University payroll system to report their Social Security number at the time of admission. Newly admitted students who do not have a Social Security number should obtain one well in advance of their first registration. International students should consult theInternational Students and Scholars Office, located at 545 W. 112th Street, 4th Floor (212-854-3587), for further information.

Special billing authorization is required of all students whose bills are to be sent to a third party for payment. Students who are not citizens of the United States and who need authorization for special billing of tuition and/or fees to foreign institutions, agencies, or sponsors should go to the International Students and Scholars Office with two copies of the sponsorship letter.

University Regulations

Each person whose enrollment has been completed is considered a student of the University during the term for which they are enrolled unless their connection with the University is officially severed by being withdrawn or for other reasons. No student enrolled in any school or college of the University shall at the same time be enrolled in any other school or college, either of Columbia University or of any other institution, without the specific authorization of the dean or director of the school or college of the University in which they are first enrolled.

The privileges of the University are not available to any student until enrollment has been completed. Students are not permitted to attend any University course for which they are not officially enrolled or for which they have not officially filed a program unless they have been granted auditing privileges.

The University reserves the right to withhold the privileges of registration and enrollment or any other University privilege from any person who has outstanding financial, academic, or administrative obligations to the University.

Continuous registration until completion of all requirements is obligatory for each degree. Students are exempted from the requirement to register continuously only when granted a leave of absence by the Committee on Academic Standing (for undergraduate students) or the Office of Engineering Student Affairs (for graduate students).

Registration Instructions

Registration instructions are announced in advance of each registration period by the Registrar. Students should consult these instructions for the exact dates and times of registration activities. Students must be sure to obtain all necessary written course approvals and advisers' signatures before registering. Undergraduate students who have not registered for a full-time course load of at least 12 credits by the end of the change of program period will be withdrawn, as will graduate students who have not registered for any coursework by the end of the change of program period. International students enrolled in graduate degree programs must maintain full-time status until degree completion.

DEGREE REQUIREMENTS AND SATISFACTORY PROGRESS

Undergraduate

Undergraduate students are required to complete the School's degree requirements and graduate in eight academic terms. Full-time undergraduate registration is defined as at least 12 credits per term. However, in order to complete the degree in 8 semesters, students must be averaging 16 credits per term. Students may not register for point loads greater than 21 points per term without approval from the Committee on Academic Standing.

To be eligible to receive the Bachelor of Science degree, a student must complete the courses prescribed in a faculty-approved major/program (or faculty-authorized substitutions) and achieve a minimum cumulative grade-point average (GPA) of 2.0. Although the minimum number of academic credits is 128 for the B.S. degree, some programs of the School require a greater number of credits in order to complete all the requirements. Undergraduate engineering degrees are awarded only to students who have completed at least 60 points of coursework at Columbia. No credit is earned for duplicate courses or for courses that are taken pass/fail and the final grade is a P, with the exception of two nontechnical electives at the 3000-level or above and physical education courses, as noted below.

Undergraduates in the programs accredited by the Engineering Accreditation Commission of ABET (Biomedical Engineering, Chemical Engineering, Civil Engineering, Earth and Environmental Engineering, Electrical Engineering, and Mechanical Engineering) satisfy ABET requirements by taking the courses in prescribed programs, which have been designed by the departments so as to meet the ABET criteria.

Graduate

Graduate students are required to complete the School's degree requirements. Full-time graduate registration is defined as at least 12 credits per term. A typical course load is 12–15 credits per term, not including the last term.

Degree requirements for master's degrees must be completed within five years; those for the doctoral degrees must be completed within seven years. Degree-seeking students must maintain continuous enrollment during academic terms (Fall and Spring) at Columbia Engineering until all degree requirements are met and their degree is scheduled for conferral. Students who fail to register by the end of the Change of Program Period will be withdrawn if they have not been authorized for a leave of absence.

Students who need more than the allowable time to complete their degree requirements or students who attempted to graduate but failed to meet degree requirements should submit a petition for a program extension to extend their studies.

A graduate student who has matriculated in a degree program is expected to (1) maintain a cumulative GPA above the minimum requirement and (2) make normal progress toward completion of their degree requirements.

A minimum cumulative GPA of 2.5 or the minimum GPA required by the academic department, whichever is higher (in all courses taken as a degree candidate), is required for the M.S. degree. A minimum GPA of 3.0 or the 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 (Ph.D.) degrees.

Normal progress toward the degree, to ensure completion of the degree within the necessary timeframe, necessitates that students earn final grades sufficient to count toward the degree in their attempted credits for the semester.

Graduate students who do not meet the minimum cumulative GPA of the school and the department or are not making sufficient progress towards their degree requirements will be placed on Academic Action. Please review the Academic Monitoring section for more information.

Changes in Registration

An undergraduate student who wishes to drop or add courses or to make other changes in their program of study after the change of program period must obtain the approval of their CSA Advising Dean. An undergraduate student who wishes to drop or add a course in their major must also obtain department approval. Graduate students who wish to drop or add a course or make other course related changes after the change of program period must obtain approval from their department and their department must submit the relevant paperwork to the Office of Engineering Student Affairs for processing. The deadline for making program changes in each term is shown in the Academic Calendar at Columbia University.

Note: the drop-date for Columbia Core courses is the the end of the change of program period for the current semester

After these dates, undergraduate students must petition the Committee on Academic Standing; graduate students must petition the Office of Engineering Student Affairs. For individual courses dropped after the end of the Change of Program period, there will be no tuition refund. Failure to attend a class will be indicated by a permanent unofficial withdrawal (UW) on the transcript.

In cases that have been referred for disciplinary action through the Dean's Discipline process, undergraduate students may not drop from the course in question without a successful petition to the Committee on Academic Standing. Graduate students should contact the Office of Engineering Student Affairs.

Transfer Credits

Undergraduate students may obtain academic credit toward the B.S. degree by completing coursework at other accredited four-year institutions. Normally, this credit is earned during the summer. To count as credit toward the degree, a course taken elsewhere must have an equivalent at Columbia University and the student must achieve a grade of at least B. An exception to this policy is made for students enrolled in an approved study abroad program. Students in an approved study abroad program will receive transfer credit if they earn a grade of C or higher. To transfer credit, a student must obtain prior approval from their CSA Advising Dean and the department before taking such courses. A course description and syllabus should be furnished as a part of the approval process. Courses taken before the receipt of the high school diploma may not be credited toward the B.S. degree. A maximum of 6 credits may be credited toward the degree for college courses taken following the receipt of a high school diploma and initial enrollment at Columbia University.

For graduate students, Advanced Standing is granted in most cases instead of transfer credits. Advanced Standing refers to a student receiving credit towards their graduate degree program for previously completed graduate-level coursework within the following parameters:

M.S. students in on-campus programs can earn Advanced Standing toward the M.S. degree for graduate-level coursework (4000 level or above) completed at Columbia University only. No more than 15 points of Advanced Standing can be awarded, and the coursework can not have been counted towards a previous degree, minor, or certificate program. Advanced Standing points must be deemed appropriate and relevant to the degree program of study, as determined by the Department or Program. In most cases, regardless of Advanced Standing points, M.S. students are required to complete a minimum of 15 credits while enrolled as a Columbia Engineering graduate student.

M.S. students in CVN programs are not eligible for Advanced Standing. They may instead request up to 6 transfer credits for prior graduate-level coursework completed at either Columbia University or another institution.

Students possessing a conferred master's degree upon entry into a Ph.D. program may be awarded 2 residence units toward their Ph.D., as well as 30 points of Advanced Standing toward their Ph.D. with approval from the academic department and the Office of Engineering Student Affairs.

Eng.Sc.D. students will earn Advanced Standing provided they earned their master's degree outside of Columbia Engineering to reflect their prior completion of an M.S. program. They can earn up to 30 points of Advanced Standing. These Advanced Standing points are separate from the points the student must complete as an Eng.Sc.D. student at Columbia Engineering.

Examinations

Midterm examinations: Instructors generally schedule these in late October and mid-March.

Final examinations: These are given at the end of each term. The Master University Examination Schedule is available online and is confirmed in November for the fall term and April for the spring term. This schedule is sent to all academic departments and is available for viewing on the Columbia website. Students should consult with their instructors for any changes to the exam schedule. Examinations will not be rescheduled to accommodate travel plans.

Note: If a student has three final examinations scheduled during one calendar day, as certified by the Registrar, an arrangement may be made with one of the student's instructors to take that examination at another, mutually convenient time during the final examination period. This rule refers to a calendar day, not a 24-hour time period. Undergraduate students unable to make suitable arrangements on their own should contact their CSA Advising Dean. Graduate students should contact the Office of Engineering Student Affairs.

Transcripts and Certifications

Information on obtaining University transcripts and certifications can be found on the Registrar's website. Please visit registrar.columbia.edu/content/transcripts-and-certifications.

Report of Grades

Grades can be viewed by using the Vergil feature located on the Student Services home page at columbia.edu/students. If you need an official printed report, you must request a transcript (please see Transcripts and Certifications above).

All graduate students must have a current mailing address on file with the Registrar's Office.

Transcript Notations

The grading system is as follows: A, excellent; B, good; C, satisfactory; D, poor but passing; F, failure (a final grade not subject to re-examination). Occasionally, P (Pass) is the only passing option available. The grade-point average is computed on the basis of the following index: A=4, B=3, C=2, D=1, F=0. Designations of + or – (used only with A, B, C) are equivalent to 0.33 (i.e., B+=3.33; B–=2.67). Grades of P, IN, UW, W, and MU will not be included in the computation of the grade-point average.

R (registration credit; no qualitative grade earned): not accepted for degree credit in any program. R credit is not available to undergraduate students for academic classes. In some divisions of the University, the instructor may stipulate conditions for the grade and report a failure if those conditions are not satisfied. The R notation will be given only to those students who indicate, upon registration and to the instructor, their intention to take the course for R, or who, with the approval of the instructor, file written notice of change of intention with the registrar not later than the last day of change of program. Students wishing to change to R credit after this date are required to submit written approval from the course instructor to the Office of Engineering Student Affairs (ESA) who will submit it to the registrar. The request to change to R credit must be made by the last day of the change of program period to change a course grading option. A course that has been taken for R credit may not be repeated later for examination credit and cannot be uncovered under any circumstances. The mark of R does not count toward degree requirements for graduate students. The mark of R is automatically given in Doctoral Research Instruction courses.

UW (unofficial withdrawal): given to students who discontinue attendance in a course but are still officially registered for it, or who fail to take a final examination without an authorized excuse.

IN (incomplete): granted only in the case of incapacitating illness as certified by the Health Services at Columbia, serious family emergency, or circumstances of comparable gravity. Undergraduate students request an IN by filling out a petition for an incomplete with their CSA Advising Dean prior to the final exam for the course in the semester of enrollment. Students requesting an IN must gain permission from both the Committee on Academic Standing (CAS) and the instructor. Graduate students should contact their instructor. If granted an IN, students must complete the required work within a period of time stipulated by the instructor but not to exceed one year. After a year, the IN will be automatically changed into an F or the contingency grade. The contingency grade is the grade that the student would earn if they completed no further work in the course, with any missing assignments counted as an F or zero.

YC (year course): a mark given at the end of the first term of a course in which the full year of work must be completed before a qualitative grade is assigned. The grade given at the end of the second term is the grade for the entire course.

CP (credit pending): given only in graduate research courses in which student research projects regularly extend beyond the end of the term.

Upon completion, a final qualitative grade is then assigned and credit allowed. The mark of CP implies satisfactory progress.

MU (make-up examination): given to a student who has failed the final examination in a course but who has been granted the privilege of taking a second examination in an effort to improve their final grade. The privilege is granted only when there is a wide discrepancy between the quality of the student's work during the term and their performance on the final examination, and when, in the instructor's judgment, the reasons justify a make-up examination. A student may be granted the mark of MU in only two courses in one term, or, alternatively, in three or more courses in one term if their total point value is not more than 7 credits. The student must remove MU by taking a special examination administered as soon as the instructor can schedule it.

P/F (pass/fail): Undergraduates may select to take only one course that is offered for a letter grade pass/fail each semester. In general, courses taken pass/fail do not count toward degree requirements including the 128-point requirement. There are two exceptions to this rule. Physical Education classes do count toward the 128 point requirement, even though students do not receive letter grades for the class. Additionally, undergraduate students may take up to two courses of the 9-11 nontechnical elective credit on a P/F basis. These courses must be at the 3000 level or higher and must be courses that can be taken P/F by students attending Columbia College (e.g., instruction classes in foreign language and core curriculum classes are not eligible to be taken pass/fail). These 3000-level non-tech elective classes may not count toward a minor if the grade remains a P. Students do have the option of uncovering the letter grade of these two elective 3000-level non-tech classes by the end of the change of program period of the following semester after the course has been completed. Any other course that is taken P/F cannot be uncovered by an undergraduate student. For these classes, the undergraduate student will have to petition the Committee on Academic Standing to uncover the letter grade. Please note that physical education classes are the only courses taught solely on a P/F basis that may apply toward the 128 credits for the degree.

For graduate students, courses taken for the P/F option do not count toward the credits necessary for a student's degree requirements. Students have until the last day to change a course grading option to elect the P/F option. After that day, there is no uncovering for a letter grade. Additionally, the grading option cannot be changed after a final grade has been assigned.

W (official withdrawal): a mark given to students who are granted a leave of absence after the drop deadline for the semester. The grade of W, meaning "official withdrawal," will be recorded as the official grade for the course in lieu of a letter grade.

Name Changes

Columbia University recognizes that some students prefer to identify themselves by a First Name and/or Middle Name, other than their Legal Name. For this reason, beginning in the Spring 2016 semester, the University has enabled students to use a "Preferred Name" where possible in the course of University business and education.

Under Columbia's Preferred Name policy, any student may choose to identify a Preferred First and/or Middle Name in addition to the Legal Name. Students may request this service via a link on SSOL. The student's Preferred Name may be used in many University contexts, including SSOL, class rosters, CourseWorks, and Canvas, and on ID Cards. For some other records, the University is legally required to use a student's Legal Name. However, whenever reasonably possible, a student's "Preferred Name" will be used. Please see registrar.columbia.edu/content/name-and-address-changes for further details.

Students may change their name of record by submitting a name change affidavit to the Student Service Center. Affidavits are available from this office or online at registrar.columbia.edu.

GRADUATION

Columbia Engineering awards degrees three times during the year: in February, May, and October. There is one Commencement ceremony for the University in May.

Students must meet all program, department, and school requirements to graduate. This includes all required courses, minimum final grades for all courses, transcripts from previous institutions, meeting the minimum GPA requirements, etc. Failure to meet the requirements will disqualify students from a degree conferral.

Application or Renewal of Application for the Degree

In order to be considered for a degree or certificate, students must file an Application for Degree or Certificate. Students should complete the online Application for Degree available directly within SSOL, under the Degree Application Status tab. For additional support, please follow the instructions on the Registrar's website. Candidates for Master of Philosophy and doctoral degrees should inquire at their departments but must also follow the instructions of the Dissertation Office.

General application deadlines to submit the Application for the Degree are November 1 for February, January 1 for May, and August 1 for October. (When a deadline falls on a weekend or holiday, the deadline moves to the next business day.) Candidates for Master of Philosophy and doctoral degrees should refer to the Dissertation Office's dissertation dates and deadlines.

Students who fail to earn the degree by the conferral date will be moved to a later conferral date.

Diplomas

There is no charge for the preparation and conferral of an original diploma. If your diploma is lost or damaged, there will be a charge of $100 for a replacement diploma. Note that replacement diplomas carry the signatures of current University officials. Applications for replacement diplomas are available on the Registrar's website: registrar.columbia.edu/registrar-forms/application-replacement-diploma. Any questions regarding graduation or diploma processing should be addressed to diplomas@columbia.edu.

ACADEMIC HONORS

Dean's List

To be eligible for Dean's List honors, an undergraduate student must achieve a grade-point average of 3.5 or better and complete at least 15 graded credits with no unauthorized incompletes, UWs, or grades lower than C.

Honors Awarded with the Degree

At the end of the academic year, a select portion of the candidates for the Bachelor of Science degree who have achieved the highest academic cumulative grade-point average are accorded Latin honors. Latin honors are awarded in three categories (cum laude, magna cum laude, and summa cum laude) to no more than 25 percent of the graduating class, with no more than 5 percent summa cum laude, 10 percent magna cum laude, and 10 percent cum laude. Honors are awarded on the overall record of graduating seniors who will have completed a minimum of four semesters at Columbia upon graduation. Students who enter Columbia through the Combined Plan program are eligible for honors based on four semesters at Columbia. Students may not apply for honors.

ACADEMIC MONITORING

The SEAS Faculty Committee on Instruction determines academic policies and regulations for the School.

The Undergraduate Committee on Academic Standing and the Office of Engineering Student Affairs are expected to uphold the policies and regulations of the Committee on Instruction and determine when circumstances warrant exceptions to them.

Academic performance is reviewed by advisers at the end of each Fall and Spring semester. The Undergraduate Committee on Academic Standing, in consultation with the departments, meets to review undergraduate grades and progress toward the degree. Indicators of academic well-being are grades that average above 2.0 each term, making adequate progress for the completion of their degree program, with no incomplete grades.

For graduate students, the Office of Engineering Student Affairs and its departments monitor the academic progress of graduate students. If a student's academic performance (based on GPA and/or degree progress) indicates cause for concern, they may be put on Academic Action and be guided toward resources and support. Examples of Academic Actions may include Academic Warning, Academic Probation, Strict Academic Probation, or Academic Dismissal.

Possible academic sanctions include:

- *Warning:* C– or below in any core science course or in a required course for their major; low points toward degree completion
- *Academic Probation:* Students will be placed on academic probation if they meet any of the conditions below:
  - – fall below a 2.0 GPA in a given semester
  - – have not completed 12 points successfully in a given semester
  - – have not completed chemistry, physics, University Writing, The Art of Engineering, and calculus during the first year
  - – receive a D, F, UW, or unauthorized Incomplete in any first-year/sophomore required courses
  - – receive a D, F, UW, or unauthorized Incomplete in any course required for the major
  - – receive straight C's in the core science courses (chemistry, calculus, physics) or in required courses for their major
  - – not making significant progress toward the degree
- *Continued Probation:* Students who are already on probation and fail to meet the minimum requirements as stated in their sanction letter.
- *Strict Probation:* Students who are already on probation, fail to meet the minimum requirements as stated in their sanction letter, and are far below minimum expectations. This sanction is typically applied when there are signs of severe academic difficulty.
- *Suspension and Dismissal:* Students who have been placed on academic probation and who fail to be restored to good academic standing in the following semester can be considered either for suspension or dismissal by

the Undergraduate Committee on Academic Standing. The decision to suspend or dismiss a student will be made by the Committee on Academic Standing in the Berick Center for Student Advising and the Dean's Office in close consultation with the student's departmental adviser when the student has declared a major. In cases of suspension, the student will be required to make up the deficiencies in their academic record by taking appropriate courses at a four-year accredited institution. Students must be able to complete their degree requirements in their eighth semester at Columbia after readmission. If this is not achievable, then students should be considered for dismissal instead.

The courses that the student must take will be determined by the Undergraduate Committee of Academic Standing and by the student's departmental adviser when the student has declared a major. All proposed courses will be reviewed by the appropriate faculty who teach the equivalent classes at Columbia University. All courses that are being taken to fulfill a major requirement or as a technical elective must be approved by the student's departmental adviser. Courses being taken to count as a nontech elective or to count as general credit would only require the approval of the student's advising dean in the Berick Center for Student Advising. The existing procedures for the approval of outside credit will be followed in these cases. Students must receive a grade of B or better for the credit to be transferred.

Students will be placed on Academic Action if their cumulative GPA is below 2.5 or the minimum GPA required by the academic department, whichever is higher. Students may also be placed on Academic Action if they are not making satisfactory progress toward their degree. Doctoral students can also be placed on Academic Action if they are not making satisfactory progress toward their dissertation and doctoral milestones. Students who are on Academic Action and do not return to good standing after one semester may be dismissed from the program.

LEAVE OF ABSENCE

A Leave of Absence is an authorized, temporary break from academic participation. Leave requests (as well as requests to return from leave) require approval from the appropriate office as outlined in detail for each request type.

MEDICAL LEAVE OF ABSENCE

Undergraduate Students

A medical leave of absence for an undergraduate student is granted by the James H. and Christine Turk Berick Center for Student Advising to an undergraduate student whose health prevents them from successfully pursuing full-time study. Undergraduates who take a medical leave of absence are guaranteed housing upon their return if they were already guaranteed housing. Students on medical leave may be eligible to continue participation in University-sponsored health insurance; please contact studentinsurance@columbia.edu for additional details.

Documentation from a physician or counselor must be provided before such a leave is granted. In order to apply for readmission following a medical leave, a student must submit proof of recovery from a physician or counselor. Please visit the CSA website for further details.

A medical leave for an undergraduate student is for a minimum of one year and cannot be longer than two years.

When a medical 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 courses that the student is enrolled in will be deleted from the student's record. If after the drop deadline, the course grades will typically result in W (Official Withdrawal) in all courses. In certain circumstances, a student may qualify for an IN (Incomplete), which would have to be completed within two semesters after the student returns to Columbia. If the Incomplete is not completed by that time, an F or contingency grade such as W will be inserted as the final grade.

In exceptional cases, an undergraduate student may apply for readmission following a one-term medical leave of absence. In addition to providing a personal statement and supporting medical documentation for the Medical Leave Readmission Committee to review, the student will also need to provide a well-developed academic plan that has been approved by the departmental adviser and their Advising Dean as part of the readmission process. This plan must demonstrate that their return to Columbia Engineering following a one-semester leave of absence will allow the student to properly follow the sequence of courses as required for the major and to meet all other graduation requirements by their eighth semester. The final decision regarding whether or not a student will be allowed to be readmitted after a one-semester leave will be made by the Medical Leave Readmission Committee.

During the course of the leave, students are not permitted to take any courses for the purpose of transferring credit and are not permitted to be on campus. For more information about the medical leave of absence policy, undergraduates should consult their CSA Advising Dean.

Graduate Students

A medical leave of absence for a graduate student is granted by the Office of Engineering Student Affairs; please consult with their office for more information.

Documentation from a physician or counselor must be provided in order for such a leave to be granted.

When a medical 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 courses that the student enrolled in will be deleted from their record. If after the drop deadline, the course grades will typically result in W (Official Withdrawal) in all courses. In certain circumstances, a student may qualify for an IN (Incomplete), which would have to be completed within two semesters after the student returns to Columbia. If the Incomplete is not completed by that time, an F or contingency grade such as W will be inserted as the final grade.

A medical leave for a graduate student is for a minimum of one semester, up to two years (or four semesters) total. If a student does not return for their approved term, they will be withdrawn from the School. Students may return in the Fall or Spring terms.

Students on medical leave may be eligible to remain in on-campus housing; please contact seas-housing@columbia.edu for additional details. Students on medical leave may be eligible to continue participation in University-sponsored health insurance; please contact studentinsurance@columbia.edu for additional details.

Graduate students requesting to return from medical leave must submit supporting medical documentation and a personal statement that includes a well-developed plan to complete their degree. Graduate students may also be required to meet with a medical provider at Columbia. Doctoral students must have a faculty advisor and funding from their faculty advisor and/or academic department prior to and when returning from an approved medical leave. It is recommended that students submit the request to return form well in advance of the semester that they wish to return for. Please note that return requests are not processed until June 1 for fall returns and November 1 for spring returns.

During the course of the leave, students are not permitted to take any courses for the purpose of transferring credit and are not permitted to be on campus.

VOLUNTARY LEAVE OF ABSENCE

A voluntary leave of absence may be granted to eligible students who require a break from their studies due to personal reasons.

Undergraduate Students

A voluntary leave of absence (VLOA) may be granted by the Committee on Academic Standing to undergraduate students who request a temporary withdrawal from Columbia Engineering for a nonmedical reason. Students considering a voluntary leave must discuss this option in advance with their CSA Advising Dean. Voluntary leaves are granted for a period of one academic year only for undergraduate students; VLOAs will ordinarily not be granted for one semester, or for more than one year. Students must be in good academic standing at the time of the leave and must be able to complete their major and degree in eight semesters. Please visit the CSA website for further details.

When a voluntary 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 specific courses that the student is enrolled in for the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be a W (Official Withdrawal) in all courses. In certain circumstances, a student may qualify for an IN (Incomplete).

In exceptional cases, an undergraduate may apply for readmission following a one-term voluntary leave of absence. The student will need to provide to the Committee on Academic Standing a well-developed academic plan that has been approved by the departmental adviser and the Berick Center for Student Advising as part of the admission process. This plan must demonstrate that their return to Columbia Engineering following a one-semester voluntary leave of absence will allow the student to properly follow the sequence of courses as required for the major and to meet all other graduation requirements by their eighth semester. The Committee on Academic Standing will review the student's academic plan and request for readmission. The deadlines for petitioning for readmission are June 1 for the fall semester and November 1 for the spring semester. Undergraduates should consult the voluntary leave of absence policy statement available on the website of the Berick Center for Student Advising for more information regarding the readmission procedures from a voluntary leave of absence.

During the course of the leave, students are not permitted to take any courses for the purpose of transferring credit and are not permitted to be on campus. For more information about the voluntary leave of absence policy, undergraduates should consult their CSA Advising Dean.

Finally, students on a voluntary leave of absence must vacate University housing and are not eligible for University-sponsored health insurance. Students who choose to take voluntary leaves are not guaranteed housing upon return to the University. Undergraduate students who go on leave during their first year and had guaranteed housing prior to their leave are guaranteed housing upon readmission. 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

Graduate Students

A voluntary leave of absence (VLOA) for a graduate student is granted by the Office of Engineering Student Affairs. Voluntary leaves are granted for a minimum of one semester, up to one year (or two semesters) total. A graduate student must have been registered for at least one semester and have a minimum cumulative 2.5 GPA to request a voluntary leave. Additionally, doctoral students must have a faculty adviser and funding from their faculty adviser and/or academic department prior to and when returning from an approved voluntary leave of absence. The deadline to request a voluntary leave for a given term is the drop deadline for that term. VLOA requests made after the drop deadline may only be granted in exceptional circumstances.

When a voluntary leave of absence is granted during the course of the semester, the semester coursework will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will result in W (Official Withdrawal) in all courses. In certain circumstances, a student may qualify for an IN (Incomplete). For graduate students, an IN would have to be completed within two semesters after the student returns to Columbia. If the Incomplete is not completed by that time, an F or contingency grade such as W will be inserted as the final grade.

Students on a voluntary leave of absence must vacate University housing and are not eligible for University-sponsored health insurance.

A graduate student may request to

return from a voluntary leave of absence for the fall or spring terms. A request to return must be made before the return semester begins. It is recommended that students submit the request to return form well in advance of the semester that they wish to return for. Please note that return requests are not processed until April 1 for fall returns/November 1 for spring returns. Please contact the Office of Engineering Student Affairs for more information.

Students may not take courses for transferable credit while on leave. Finally, students who choose to take voluntary 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 the school.

UNDERGRADUATE EMERGENCY FAMILY LEAVE OF ABSENCE

Undergraduate 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 specific courses that the student is enrolled in for the semester will be deleted if the leave begins prior to the drop deadline. If after the drop deadline, the course grades will normally be W (official withdrawal) in all courses. In certain circumstances, a student may qualify for an Incomplete, which would have to be completed by the first week of the semester in which the student returns to Columbia. If the Incomplete is not completed by that time, a W will be inserted.

To return, students must notify the Berick Center for Student Advising as soon as possible, ideally by November 1 for the spring semester and June 1 for the fall semester. Students must request readmission in writing and submit a statement describing their readiness to return. Students who were guaranteed housing prior to taking an emergency family leave are guaranteed housing upon readmission. Students may request permission to return after one semester as long as they can demonstrate that they can remain in sequence with their coursework and have the prior approval of the departmental adviser. This plan must demonstrate that their return to Columbia Engineering following a one-semester leave of absence will allow the student to properly follow the sequence of courses as required for the major and to meet all other graduation requirements by their eight semester.

LEAVE FOR MILITARY DUTY

Please refer to the Military Leave of Absence Policy in *University Policies* at universitypolicies.columbia.edu for recent updates regarding leave for military duty.

INVOLUNTARY LEAVE OF ABSENCE POLICY

Please refer to the Involuntary Leave of Absence Policy in *University Policies* at universitypolicies.columbia.edu.

WITHDRAWAL

Students may withdraw if they wish to permanently discontinue their program of study. Students are strongly recommended to consult their advisor and/or Department prior to withdrawal.

Students who withdraw during a semester before the drop deadline have the semester coursework deleted. If after the drop deadline, the course grades will result in W (Official Withdrawal) in all courses.

Students who withdraw must vacate University housing and forfeit University-sponsored insurance.

READMISSION

Students who withdrew or were withdrawn may be eligible to apply for readmission to the school. Specific readmission procedures are determined by the reasons for and timeframe of the withdrawal.

Students who decide not to return must notify the James H. and Christine Turk Berick Center for Student Advising of their decision. The date of separation for the leave of absence will be the date of separation for withdrawal. Leaves may not extend beyond four semesters. Students who do not notify the Berick Center for Student Advising of their intentions by the end of the two-year period will be permanently withdrawn.

Further information for undergraduate students is available in the Berick Center for Student Advising. Undergraduate students applying for readmission should complete all parts of the appropriate readmission procedures by June 1 for the fall term or November 1 for the spring term.

Graduate students applying for readmission must complete a change of status application and should consult the Office of Engineering Student Affairs for additional information. Students are only eligible if their withdrawal date is within one year of their readmission request. Students who were withdrawn from the school due to a dismissal are not eligible to apply for readmission. Readmission requests should be submitted for the next commencing Fall or Spring term. Requests are not processed until April 1 for fall returns/ November 1 for spring returns.

Readmission is not guaranteed - such requests are reviewed by the student's academic department and the Office of Engineering Student Affairs. Students who fail to apply for readmission within the outlined one-year timeframe can only return to the school by submitting an application to the Office of Graduate Admissions. Submitting an admission application does not guarantee reinstatement and is subject to review by the Department and the School's admissions committees.

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 disciplinary warning 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 of the classroom.

Students rarely set out with the intent of engaging in violations of academic integrity. But classes are challenging at Columbia, and students may find themselves pressed for time, unprepared for an assignment or exam, or feeling that the risk of earning a poor grade outweighs the need to be thorough. Such circumstances lead some students to behave in a manner that compromises the integrity of the academic community, disrespects their instructors and classmates, and deprives them of an opportunity to learn. Students who find themselves in such circumstances should immediately contact their instructor and adviser for advice.

For undergraduate students, another resource is the Academic section of the Live Well | Learn Well site at wellbeing.columbia.edu/resources for Academic resources and support.

The easiest way to avoid academic integrity issues is to prepare yourself as best you can. Below are some basic suggestions to help:

- Discuss with each of your faculty their expectations for maintaining academic integrity.
- Understand that you have a student responsibility to uphold academic integrity based on the expectations outlined in each of your course syllabi.
- Understand instructors' criteria for academic integrity and their policies on citation and group collaboration.
- Clarify any questions or concerns about assignments with instructors as early as possible.
- Develop a timeline for drafts and final edits of assignments and begin preparation in advance.
- Avoid plagiarism: acknowledge people’s opinions and theories by carefully citing their words and always indicating sources.
- Assume that collaboration in the completion of assignments is prohibited unless specified by the instructor.
- Utilize the campus's resources, such as the Berick Center for Student Advising, Counseling and Psychological Services (CPS), and Engineering Student Affairs if feeling overwhelmed, burdened or pressured.
- Attend Academic Integrity workshops offered throughout the academic year.
- If you suspect that an academic integrity violation may have occurred, know that you can talk to your instructor, Advising Dean, Director of Academic Integrity, Office of Engineering Student Affairs, or the Student Conduct and Community Standards Office to report any allegations of academic misconduct.

Students found responsible of an academic integrity violation may not be eligible to receive Latin Honors at Class Day or ineligible to take on leadership positions for a period of time and/or other distinctions.

Plagiarism and Acknowledgment of Sources

Columbia has always believed that writing effectively is one of the most important goals a college student can achieve. Students will be asked to do a great deal of written work while at Columbia, for instance: term papers, coding problem sets, seminar presentations, laboratory reports, and analytical essays of different lengths. These papers play a major role in course performance, but more importantly, they play a major role in intellectual development. Columbia's academic integrity policy in the Standards & Discipline defines plagiarism as “the use of words, phrases, or ideas belonging to the student, without properly citing or acknowledging the source, is prohibited. This may include, but is not limited to, copying computer programs for the purposes of completing assignments for submission.”

One of the most prevalent forms of plagiarism involves students using information from the Internet without proper citation. While the Internet can provide a wealth of information, sources obtained from the web must be properly cited just like any other source. If you are uncertain how to properly cite a source of information that is not your own, whether from the Internet or elsewhere, it is critical that you do not hand in your work until you have learned the proper way to use in-text references, footnotes, and bibliographies. Faculty members or Teaching Assistants are available to help as questions arise about proper citations, references, and the appropriateness of group work on assignments. Students can also check with the Writing Center directly. Another option is to connect with Research Librarians who facilitate monthly citation management workshops online and in person. Information on these workshops is posted online on the Columbia Libraries website. Undergraduate students can also meet with the Director of Academic Integrity to review citation styles or options for academic support by emailing ugrad-integrity@columbia.edu. Graduate students should consult with the Office of Engineering Student Affairs in 530 Mudd or by emailing seas-conduct@columbia.edu. Ignorance of proper citation methods or academic integrity policies does not exonerate one from responsibility.

Personal Responsibility, Finding Support, and More Information

A student’s education at Columbia University consists of two complementary components: a mastery over intellectual material within a discipline and the overall development of moral character and personal ethics. Participating in forms of academic dishonesty violates the standards of our community at Columbia and severely inhibits a student’s chance to grow academically, professionally, and socially. As such, Columbia’s approach to academic integrity is informed by its explicit belief that students must take full responsibility for their actions, meaning you will need to make informed choices inside and outside the classroom. Columbia offers a wealth of resources to help students make sound decisions regarding academics, extracurricular activities, and personal issues. Undergraduate students should consult their Advising Dean or meet with the Director of Academic Integrity in Suite 601 in Lerner Hall. Graduate students should consult the Office of Engineering Student Affairs in 530 Mudd.

Academic Integrity Policies and Expectations

Violations of policy may be intentional or unintentional and may include dishonesty in academic assignments or in dealing with University officials, including faculty and staff members. Moreover, dishonesty during the Dean’s Discipline hearing process may result in more serious consequences.

Types of academic integrity violations:

- Academic Dishonesty, Facilitation of: assisting another student in a violation of academic integrity is prohibited. This may include but is not limited to selling and/or providing notes, exams, and papers.
- Assistance, Unauthorized Giving: unauthorized assistance to another student or receiving unauthorized aid from another person on tests, quizzes, assignments, or examinations without the instructor's express permission is prohibited.
- Bribery: offering or giving any favor or thing of value for the purpose of improperly influencing a grade or other evaluation of a student in an academic program is prohibited.
- Cheating: wrongfully using or attempting to use unauthorized materials, information, study aids, or the ideas or work of another in order to gain an unfair advantage is prohibited. Cheating includes, but is not limited to, using or consulting unauthorized materials or using unauthorized equipment or devices on tests, quizzes, assignments, or examinations, working on any examination, text, quiz, or assignment outside the time constraints imposed, the unauthorized use of prescription medication to enhance academic performance, and /or submitting an altered examination or assignment to an instructor for regrading.
- Collaboration, Unauthorized: collaborating on academic work without the instructor's permission is prohibited. This includes, but is not limited to, unauthorized collaboration on tests, quizzes, assignments, labs, and projects.
- Dishonesty: falsification, forgery, or misrepresentation of information to any University official in order to gain an unfair academic advantage in coursework or lab work, on any application, petition, or documents submitted to this University is prohibited. This includes, but is not limited to, falsifying information on a resume, fabrication of credentials or academic records, misrepresenting one's own research, providing false or misleading information in order to be excused from classes or assignments, and/or intentionally underperforming on a placement exam.
- Ethics, Honor Codes, and Professional Standards, Violation of: any violation of published institutional policies related to ethics, honor codes, or professional standards of a student's respective school is prohibited.
- Failing to Safeguard Work: failure to take precautions to safeguard one's own work is prohibited.
- Giving or Taking Academic Materials,

Unauthorized: unauthorized circulation or sharing of past or present course material(s) without the instructor's express permission is prohibited. This includes, but is not limited to, assignments, exams, lab reports, notebooks, and papers.

- Obtaining Advanced Knowledge: unauthorized advanced access to exams or other assignments without an instructor's express permission is prohibited.
- Plagiarism: the use of words, phrases, or ideas belonging to another without properly citing or acknowledging the source is prohibited. This may include, but is not limited to, copying computer programs for the purposes of completing assignments for submission.
- Sabotage: inappropriately and deliberately harming someone else's academic performance is prohibited.
- Self-Plagiarism: using any material portion of an assignment to fulfill the requirements of more than one course without the instructor's express permission is prohibited.
- Test Conditions: violations of compromising a testing environment or violating specified testing conditions, to intentionally or unintentionally create access to an unfair advantage for oneself or others is prohibited.

DISCIPLINARY PROCEDURES

Many policy violations that occur in the residence halls or within fraternity and sorority housing are handled by the Office of Residential Life. More serious offenses are referred directly to Student Conduct and Community Standards. Violations in University Apartment Housing are handled by building managers and housing officials. Some incidents regarding graduate students are referred directly to the School's housing liaison in the Office of Engineering Student Affairs.

In matters involving rallies, picketing, and other mass demonstrations, the Rules of University Conduct outlines procedures.

Dean's Discipline Process for Undergraduate and Graduate Students

It is expected that all students act in an honest way and respect the rights of others at all times. Dean's Discipline is the process utilized to investigate and respond to allegations of behavioral or academic misconduct. The Dean's Discipline process is not meant to be an adversarial or legal process but instead aims to educate students about the impact their behavior may have on their own lives as well as on the greater community.

The process is initiated when an allegation is reported that a student may have violated University policies. Students may be subject to Dean's Discipline for any activity that occurs on or off campus that impinges on the rights of other students and community members. This also includes violations of local, state, or federal laws.

Student Conduct and Community Standards is responsible for administering the Dean's Discipline disciplinary process concerning undergraduate students that are not reserved to some other body. The Office of Engineering Student Affairs is responsible for all disciplinary affairs concerning graduate students that are not reserved to some other body.

Students are expected to familiarize themselves with the Standards and Discipline handbook and the policies and expectations available on the Students Conduct and Community Standards website at cssi.columbia.edu, which is part of the required Academic Integrity Tutorial modules in CourseWorks. The Bulletin is also not to be considered the sole or comprehensive guide to policies at Columbia. Students should consult the policies and expectations of the various offices and departments for additional guidance.

Students found responsible for reportable violations of conduct, including academic integrity violations, will need to report such offenses on future recommendations for law, medical, or graduate school. Students found responsible for any violations of conduct may be disqualified from receiving Latin Honors or other awards. They may also be disqualified from participating in internships or other leadership roles. The parents or guardians of undergraduate students may also be notified in cases of receiving a sanctioned outcome of Disciplinary Probation or higher.

For more information about the discipline process for undergraduate students, please review the Academic Integrity website or Student Conduct & Community Standards. For more information about the discipline process for graduate students, please contact the Office of Engineering Student Affairs.

Confidentiality

Privacy and Reporting: Disciplinary proceedings conducted by the University are subject to the Family Education Rights and Privacy Act ("FERPA," also called "The Buckley Amendment"). There are several important exceptions to FERPA that will allow the University to release information to third parties without a student's consent. For example, the release of student disciplinary records is permitted without prior student consent to University officials with a legitimate educational interest such as a student's academic adviser, and to Columbia Athletics if the student is an athlete. The University will also release information when a student gives written permission for information to be shared. To obtain a FERPA waiver, please visit columbia.edu/cu/studentconduct/documents/FerpaRelease.pdf. To read more about the exceptions that apply to the disclosure of student records information, please visit: the University Policies website at universitypolicies.columbia.edu.

Directory of University Resources

HOMER · HERODOTUS · SOPHOCLES · PLATO · ARISTOTLE · DEMOSTHENES · CICERO

COLUMBIA UNIVERSITY RESOURCE LIST

UNDERGRADUATE ADMISSIONS

Undergraduate Admissions
212 Hamilton, MC 2807
212-854-2522
ugrad-ask@columbia.edu
undergrad.admissions.columbia.edu

UNDERGRADUATE ADVISING

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

UNDERGRADUATE STUDENT LIFE

505–515 Lerner, MC 2601
212-854-3612
cc-seas.columbia.edu/studentlife

Multicultural Affairs
505 Lerner, MC 2607
212-854-0720
cc-seas.columbia.edu/OMA

Intercultural Resource Center (IRC)
552 West 114th Street, MC 5755
212-854-0720
cc-seas.columbia.edu
multicultural/aboutus/irc.php

Residential Life
515 Lerner, MC 4205
212-854-3612
cc-seas.columbia.edu/reslife

Student Engagement
515 Lerner, MC 2601
212-854-3612
cc-seas.columbia.edu/engagement

COLUMBIA COLLEGE

208 Hamilton, MC 2805
212-854-2441
college.columbia.edu

CORE CURRICULUM PROGRAM

Center for the Core Curriculum
202 Hamilton, MC 2811
212-854-2453
college.columbia.edu/core

Art Humanities
826 Schermerhorn, MC 5517
212-854-4505
arthum.college.columbia.edu

Music Humanities
621 Dodge, MC 1813
212-854-3825
college.columbia.edu/core/classes/mh.php

Contemporary Civilization
514 Fayerweather, MC 2811
212-854-5682
college.columbia.edu/core/conciv

Literature Humanities
202 Hamilton, MC 2811
212-854-2453
college.columbia.edu/core/lithum

Undergraduate Writing Program
310 Philosophy, MC 4995
212-854-3886
uwp@columbia.edu
college.columbia.edu/core/uwp

ENGINEERING STUDENT AFFAIRS

Graduate Student Affairs
530 S. W. Mudd, MC 4708
212-854-6438
seas-gsa@columbia.edu
gradengineering.columbia.edu

Graduate Admissions
1220 S. W. Mudd, MC 4708
212-854-4688
gradmit@columbia.edu
gradengineering.columbia.edu/admissions

COLUMBIA VIDEO NETWORK

540 S. W. Mudd, MC 4719
212-854-6447
info@cvn.columbia.edu
cvn.columbia.edu

CAREER SUPPORT

Center for Career Education (Undergraduates)
East Campus, Lower Level, MC 5727
212-854-5609
careereducation@columbia.edu
careereducation.columbia.edu

Graduate Career Placement Center
646-832-5941

seas-gcp@columbia.edu
career.engineering.columbia.edu

COMPUTING SUPPORT CENTER

Client Services Help Desk
202 Philosophy, MC 4926
212-854-1919
askcuit@columbia.edu
cuit.columbia.edu

THE EARL HALL CENTER

University Chaplain
Office: W710 Lerner
Mailing: 202 Earl Hall, MC 2008
212-854-6242, 212-854-1493
ouc.columbia.edu

EQUAL OPPORTUNITY AND AFFIRMATIVE ACTION

103 Low Library, MC 4333
212-854-5511
eoaa.columbia.edu

Student Services for Gender-Based and Sexual Misconduct
800 Watson Hall
212-854-1717
genderbasedmisconduct.columbia.edu

FINANCIAL AID (UNDERGRADUATE)

Undergraduate Financial Aid and Educational Financing
618 Lerner
Mailing: 100 Hamilton, MC 2802
212-854-3711
ugrad-finaid@columbia.edu
cc-seas.financialaid.columbia.edu

FINANCIAL AID (GRADUATE)

Student Financial Planning
615 Lerner, MC 2802
212-854-7040
sfp@columbia.edu
sfs.columbia.edu/financial-aid/graduate

Institutional Financial Aid (Grants, Fellowships, Assistantships)
Office of Engineering Student Affairs
530 S. W. Mudd, MC 4708
212-854-6438

GLOBAL ENGAGEMENT

Center for Undergraduate Global Engagement (UGE)
606 Kent Hall, MC 3948
212-854-2559
uge@columbia.edu
global.undergrad.columbia.edu

COLUMBIA HEALTH

General Info: 212-854-2284
health@columbia.edu
health.columbia.edu

CU-EMS (Ambulance)
212-854-5555

Insurance and Immunization Compliance
John Jay, 3rd Floor, MC 3601
Insurance Office: 212-854-3286
studentinsurance@columbia.edu
Immunization Compliance Office:
212-854-7210
immunizationcompliance@columbia.edu

Student Health Insurance Plan Administrators
Aetna Student Health
1-800-859-8471
www.aetnastudenthealth.com/columbia

Alice! Health Promotion
John Jay, 3rd Floor, MC 3601
212-854-5453
alice@columbia.edu

Counseling and Psychological Services
Lerner, 8th floor, MC 2606
24/7 Support: 212-854-2878

Disability Services
108A Wien Hall, MC 3711
Voice/TTY: 212-854-2388
disability@columbia.edu

Medical Services
John Jay Hall, 4th Floor
212-854-6655 (Gay Health Advocacy Project)
24/7 Support: 212-854-7426

Sexual Violence Response
Lerner, 7th floor
24/7 Support: 212-854-HELP (4357)
SVResponse@cumc.columbia.edu

HOUSING AND DINING

Columbia Housing
118 Hartley, MC 3003
212-854-2946
housing@columbia.edu
housing.columbia.edu

Columbia Dining
118 Hartley, MC 3003
212-854-4076
dining@columbia.edu
dining.columbia.edu

INTERCOLLEGIATE ATHLETICS AND PHYSICAL EDUCATION

Dodge Physical Fitness Center
212-854-7149
perec.columbia.edu

INTERNATIONAL STUDENTS AND SCHOLARS (ISSO)

Office: 524 Riverside Drive, Ground Floor
Mailing: 2960 Broadway, MC 5724
212-854-3587
isso@columbia.edu
isso.columbia.edu

LIBRARIES

Butler Library Information
535 W. 114th Street
212-854-7309
library.columbia.edu

Science & Engineering Library
401 Northwest Corner
212-851-2950

MATH/SCIENCE DEPARTMENTS

Biological Sciences
600 Fairchild, MC 2402
212-854-4581

Chemistry
344 Havemeyer, MC 3178
212-854-2202

Earth and Environmental Sciences
106 Geoscience, Lamont-Doherty Earth Observatory, 845-365-8550

Mathematics
410 Mathematics, MC 4426
212-854-2432

Physics
704 Pupin, MC 5255
212-853-1320

Statistics
1255 Amsterdam Avenue
Room 1005 SSW, MC 4690
212-851-2132

OMBUDS OFFICE

660 Schermerhorn Ext., MC 5558
212-854-1234
ombuds@columbia.edu
ombuds.columbia.edu

On Wednesdays the Ombuds Officer is at the Columbia Medical Center office:
154 Haven Ave. Room 412
212-304-7026

PROFESSIONAL DEVELOPMENT AND LEADERSHIP

255 Engineering Terrace
646-761-1694
seas-pdl@columbia.edu
pdl.engineering.columbia.edu

PUBLIC SAFETY

101 Low Library, MC 4301
212-854-2797 (24 hours a day)
publicsafety@columbia.edu
publicsafety.columbia.edu

Campus Emergencies:
212-854-5555

Escort Service:
212-854-SAFE (7233)

REGISTRAR

210 Kent, MC 9202
registrar@columbia.edu
registrar.columbia.edu

STUDENT CONDUCT AND COMMUNITY STANDARDS

800 Watson Hall
612 West 115 Street, MC 2611
212-854-6872
CSSI@columbia.edu
cssi.columbia.edu

STUDENT SERVICE CENTER

210 Kent, MC 9202
212-854-4400
ssc@columbia.edu
ssc.columbia.edu

UNIVERSITY LIFE

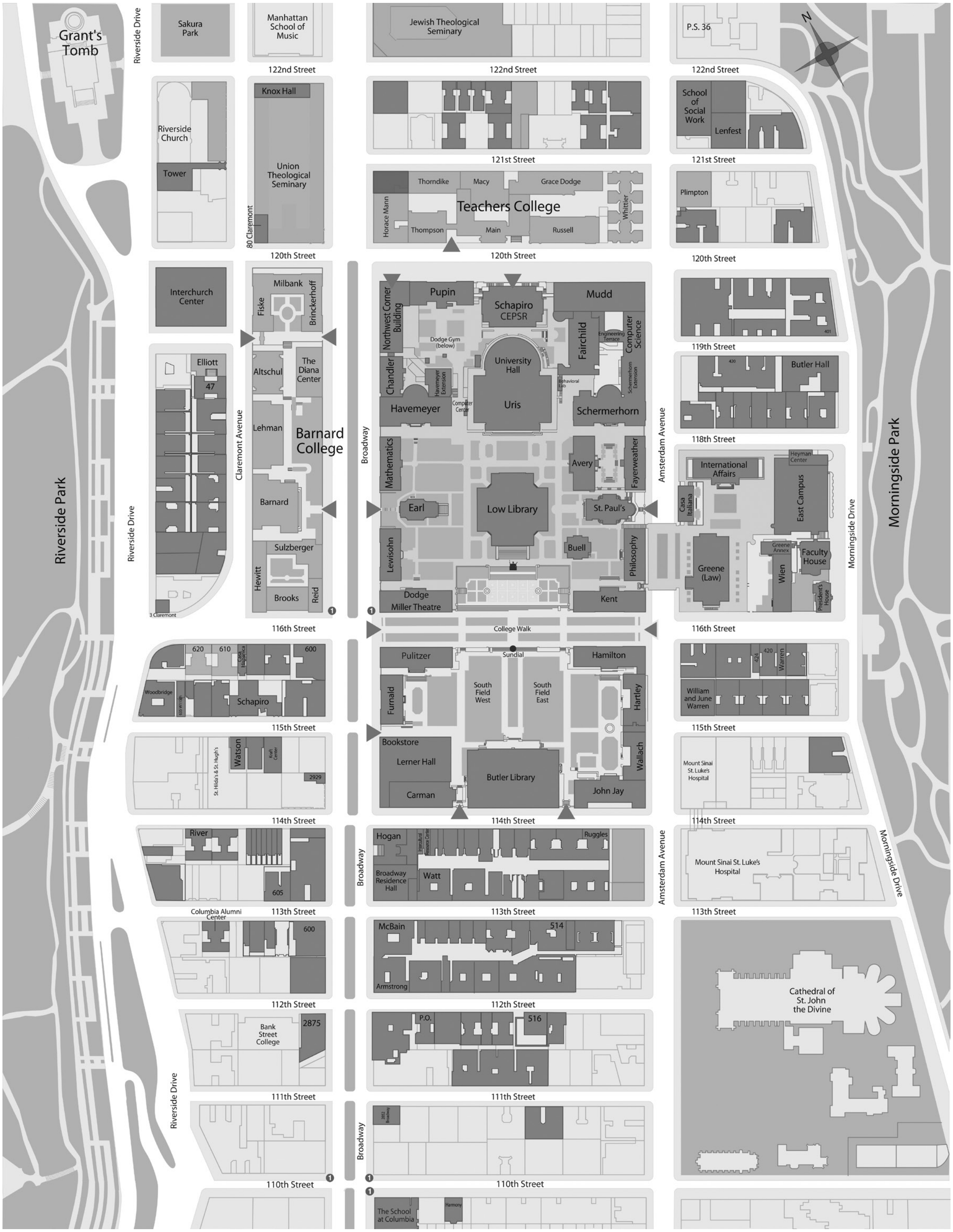
212-853-1628
UniversityLife@columbia.edu
universitylife.columbia.edu

WELLNESS

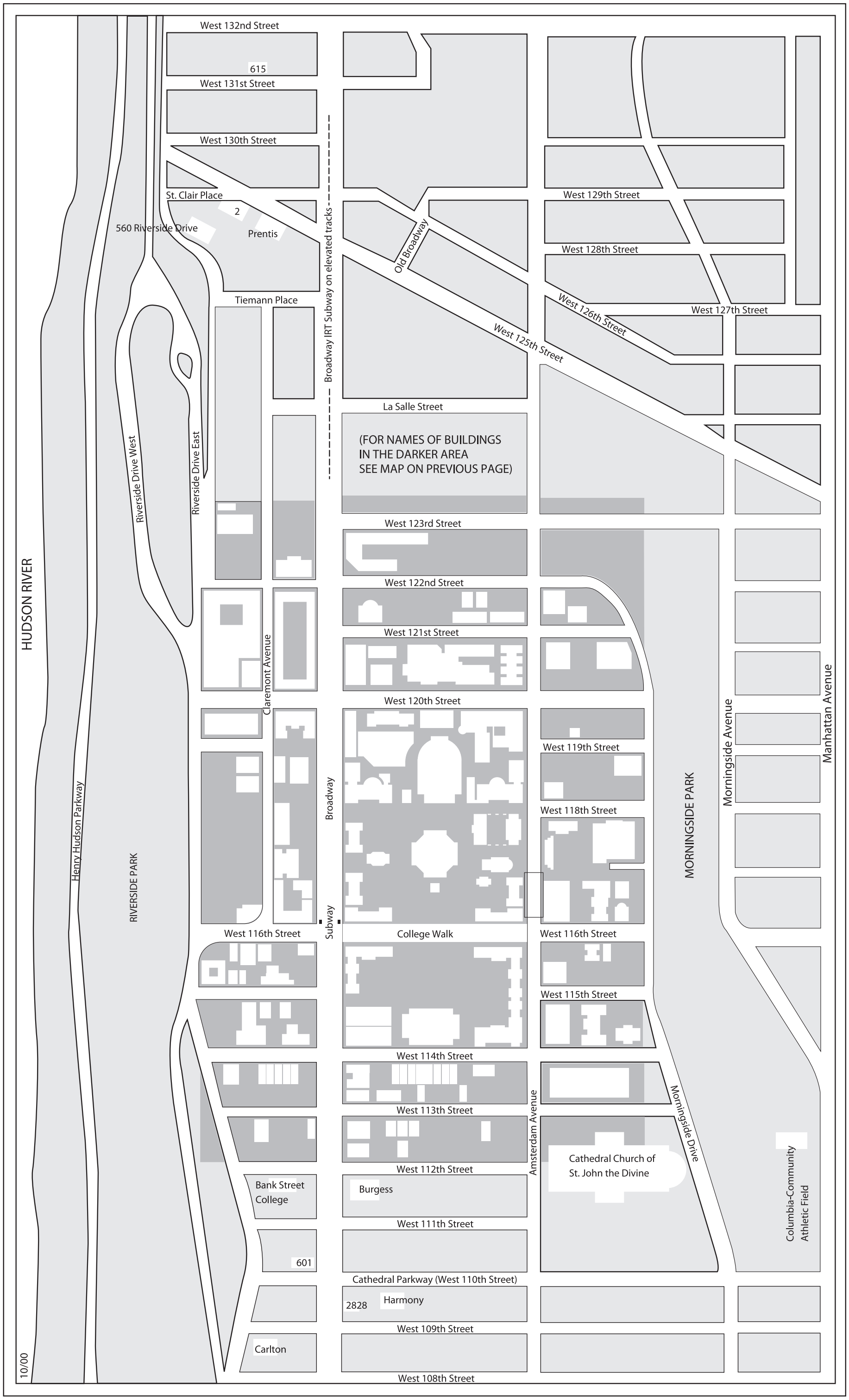
Engineering Graduate Wellness:
530 Mudd
212-854-6438
seas-wellness@columbia.edu
wellness.engineering.columbia.edu

Undergraduate Wellness:
Stephanie King
605 Lerner
212-853-1369
sk3296@columbia.edu

COLUMBIA UNIVERSITY
THE MORNINGSIDE CAMPUS & ENVIRONS


Grant's Tomb
Riverside Drive
Sakura Park
Manhattan School of Music
Jewish Theological Seminary
P.S. 36
N
122nd Street
Knox Hall
Riverside Church
Tower
Union Theological Seminary
80 Claremont
School of Social Work
Lenfest
121st Street
Thorndike
Macy
Grace Dodge
Teachers College
Horace Mann
Thompson
Main
Russell
Whittier
Plimpton
120th Street
Interchurch Center
Milbank
Fiske
Brinckerhoff
Northwest Corner Building
Pupin
Schapiro CEPSR
Mudd
Dodge Gym (below)
Engineering Terrace
Computer Science
University Hall
Fairchild
Chandler
Havemeyer Extension
Schermerhorn Extension
Behavioral Lab
Uris
Havemeyer
Computer Center
Schermerhorn
119th Street
Butler Hall
420
401
118th Street
Elliott
47
Altschul
The Diana Center
Lehman
Barnard College
Barnard
Sulzberger
Hewitt
Brooks
Reid
Claremont Avenue
Broadway
Mathematics
Avery
Fayerweather
Amsterdam Avenue
Earl
Low Library
St. Paul's
Buell
Lewisohn
Philosophy
Dodge Miller Theatre
Kent
International Affairs
Heyman Center
Casa Italiana
East Campus
Greene (Law)
Greene Annex
Wien
Faculty House
President's House
Morningside Drive
Morningside Park
Riverside Park
3 Claremont
116th Street
College Walk
Sundial
Pulitzer
Hamilton
620
610
600
Casa Hispánica
Woodbridge
635 W 115th
Schapiro
Furnald
South Field West
South Field East
Hartley
420
424
Warren
William and June Warren
115th Street
Bookstore
Watson
St. Hilda's & St. Hugh's
Kraft Center
2929
Lerner Hall
Carman
Butler Library
Wallach
John Jay
Mount Sinai St. Luke's Hospital
114th Street
River
605
Hogan
Broadway Residence Hall
Watt
Ruggles
Mount Sinai St. Luke's Hospital
Columbia Alumni Center
113th Street
600
McBain
514
Armstrong
Cathedral of St. John the Divine
112th Street
Bank Street College
2875
P.O.
516
111th Street
3022 Broadway
110th Street
The School at Columbia
Harmony
1

THE MORNINGSIDE HEIGHTS AREA OF NEW YORK CITY


West 132nd Street
615
West 131st Street
West 130th Street
St. Clair Place
2
560 Riverside Drive
Prentis
Tiemann Place
Broadway IRT Subway on elevated tracks
Old Broadway
West 129th Street
West 128th Street
West 127th Street
West 126th Street
West 125th Street
La Salle Street
(FOR NAMES OF BUILDINGS
IN THE DARKER AREA
SEE MAP ON PREVIOUS PAGE)
Riverside Drive West
Riverside Drive East
HUDSON RIVER
West 123rd Street
West 122nd Street
West 121st Street
Claremont Avenue
West 120th Street
West 119th Street
West 118th Street
Broadway
MORNINGSIDE PARK
Morningside Avenue
Manhattan Avenue
Henry Hudson Parkway
RIVERSIDE PARK
Subway
West 116th Street
College Walk
West 116th Street
West 115th Street
West 114th Street
West 113th Street
Morningside Drive
Amsterdam Avenue
Cathedral Church of
St. John the Divine
West 112th Street
Bank Street
College
Burgess
West 111th Street
601
Columbia-Community
Athletic Field
Cathedral Parkway (West 110th Street)
2828
Harmony
West 109th Street
Carlton
10/00
West 108th Street