ENGINEERING & APPLIED SCIENCE

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APPLIED PHYSICS

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Associate Professors  Michael Choma (Biomedical Engineering), Peter Rakich

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BIOMEDICAL ENGINEERING

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**Associate Professors** Fadi Akar,* Stuart Campbell, Julius Chapiro, Tarek Fahmy, Gigi Galiana,* Michael Higley,* Ansel Hillmer,* Chenxiang Lin,* Kathryn Miller-Jensen, Michael Murrell, Dana Peters,* Yibing Qyang*

**Assistant Professors** Sanjay Aneja,* Daniel Coman,* Purushottam Dixit,* Nicha Dvornek,* Evelyn Lake, Michael Mak, John Onofrey, Cristina Rodriguez, Shreya Saxena, Dustin Scheinost*

* A secondary appointment with primary affiliation in another department or school.
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CHEMICAL AND ENVIRONMENTAL ENGINEERING

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COMPUTER SCIENCE

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Assistant Professors Ian Abraham,* Kim Blenman,* Arman Cohan, Yongshan Ding, Benjamin Fisch, Tesca Fitzgerald, Julian Jara-Ettinger,* Anurag Khandelwal, Quanquan Liu, Tom McCoy,* Daniel Rakita, Katerina Sotiraki, David van Dijk,* Marynel Vázquez, Andre Wibisono, Alex Wong, Zhitao Ying, Manolis Zampetakis

Senior Lecturers James Glenn, Stephen Slade

Lecturers Timos Antonopoulos, Timothy Barron, Ozan Erat, Kyle Jensen,* Janet Kayfetz, Jay Lim, Dylan McKay, Cody Murphey, Sohee Park, Scott Petersen, Brad Rosen, Alan Weide, Cecillia Xie

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ELECTRICAL AND COMPUTER ENGINEERING

Chair Jung Han

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Associate Professors Amin Karbasi, Jakub Szefer

Assistant Professors Dionysis Kalogerias, Mengxia Liu, Owen Miller,* Priyadarshini Panda, Shreya Saxena*

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MECHANICAL ENGINEERING AND MATERIALS SCIENCE

Chair Udo Schwarz

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Associate Professors Rebecca Kramer-Bottiglio, Madhusudhan Venkadesan

Assistant Professors Ian Abraham, Yimin Luo, Amir Pahlavan, Diana Qiu, Cong Su, Daniel Wiznia∗

Senior Lecturer Beth Anne Bennett

Lecturers Joran Booth, Lawrence Wilen, Joseph Zinter

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Programs of study are offered in the areas of applied mechanics, applied physics, computer science, mechanical engineering and materials science, chemical and environmental engineering, electrical engineering, biomedical engineering, and personalized medicine and applied engineering. All programs are under the School of Engineering & Applied Science.

APPLIED PHYSICS

Fields of Study

Fields include areas of theoretical and experimental condensed-matter and materials physics, optical and laser physics, quantum engineering, and nanoscale science. Specific programs include surface and interface science, first principles electronic structure methods, photonic materials and devices, complex oxides, magnetic and superconducting artificially engineered systems, quantum computing and superconducting device research, quantum transport and nanotube physics, quantum optics, and random lasers.

BIOMEDICAL ENGINEERING

Fields of Study

Biological and medical devices, biological signals and sensors, biomaterials, biophotonics, cellular biomechanics, computational biomechanics, computational medicine, computer vision, digital image analysis and processing, drug delivery, energy metabolism, experimental biomechanics, gene delivery, gene therapy, image analysis, Magnetic Resonance Imaging (MRI), Magnetic Resonance Spectroscopy (MRS), modeling in mechanobiology, molecular biomechanics, nanomedicine, network analysis, neuroreceptors, physics of image formation (MRI, optics, ultrasound, nuclear medicine, and X-ray), physiology and human factors engineering, Positron Emission Tomography (PET), regenerative medicine, signaling pathways, Single Photon Emission Computed Tomography (SPECT), systems biology, systems medicine, tissue engineering, tracer kinetic modeling, and vascular biology.
CHEMICAL AND ENVIRONMENTAL ENGINEERING

Fields of Study

Fields include nanomaterials, polymers, interfacial phenomena, energy, water and air quality, environmental microbiology, carbon capture, and sustainability.

COMPUTER SCIENCE

Fields of Study

Algorithms and computational complexity, artificial intelligence, data networking, databases, graphics, machine learning, programming languages, robotics, scientific computing, security and privacy, and systems.

ELECTRICAL AND COMPUTER ENGINEERING

Fields of Study

Fields include biomedical sensory systems, communications and signal processing, neural networks, control systems, wireless networks, sensor networks, microelectromechanical and nanomechanical systems, nanoelectronic science and technology, optoelectronic materials and devices, semiconductor materials and devices, quantum and nonlinear photonics, quantum materials and engineering, computer engineering, computer architecture, hardware security, neuromorphic computing, and VLSI design.

MECHANICAL ENGINEERING AND MATERIALS SCIENCE

Fields of Study

**Fluids and thermal sciences**  Electrospray theory and characterization; electrical propulsion applications; aerodynamic instrumentation for separation of clusters and aerosol particles; heterogeneous nucleation in the gas phase; combustion and flames; computational methods for fluid dynamics and reacting flows; interfacial flows and instabilities and transport phenomena in disordered media.

**Soft matter/complex fluids**  Jamming and slow dynamics in gels, glasses, and granular materials; mechanical properties of soft and biological materials; rheology and statistical mechanics of muscle; structure and dynamics of proteins and other macromolecules and wetting of soft solids, elastocapillarity, poroelasticity, microrheology and scattering.

**Materials science**  Studies of structure-property-processing relationships; thin films; nanoscale effects on electronic, optical, and emergent properties of two-dimensional layered materials; picoscale characterization and engineering; correlated electron systems; molecular beam epitaxy; metallic glasses; sustainable metallurgy; data centered research approaches; nanomaterials; characterization of crystallization and other phase transformations; nanoimprinting; atomic-scale investigations of surface interactions and properties; classical and quantum nanomechanics; nanostructured energy applications; combinatorial materials science; data science in materials science; materials genome; scanning probe microscopy; theoretical spectroscopy and computational materials science; and halide perovskites.
Robotics/mechatronics  Machine and mechanism design; dynamics and control; robotic grasping and manipulation; legged locomotion; multi-agent search and exploration; optimal control for learning; model-predictive control; reinforcement learning; human-machine interface; rehabilitation robotics; haptics; soft robotics; flexible and stretchable electronics; soft material manufacturing; responsive material actuators; artificial muscle; soft-bodied control; electromechanical energy conversion; biomechanics of human movement and human-powered vehicles.

Bioengineering  Engineering sciences of living systems; biomolecular structure; biomechanics; motor control; animal locomotion; cell and tissue mechanics; biomaterials and therapeutics; human health and orthopaedics; bio-inspired computation and design; biomaterials and cell-material interaction.

INTEGRATED GRADUATE PROGRAM IN PHYSICAL AND ENGINEERING BIOLOGY (PEB)

Students applying to the Ph.D. program in Applied Physics, Biomedical Engineering, Chemical and Environmental Engineering, and Mechanical Engineering and Materials Science may also apply to be part of the PEB program. See the description under Non-Degree-Granting Programs, Councils, and Research Institutes for course requirements, and http://peb.yale.edu for more information about the benefits of this program and application instructions.

QUANTUM MATERIALS SCIENCE AND ENGINEERING (QMSE)

Students applying to the Ph.D. program in Applied Physics or Mechanical Engineering and Materials Science may also apply to be part of the QMSE program. See the description under Non-Degree-Granting Programs, Councils, and Research Institutes for course requirements.

SPECIAL REQUIREMENTS FOR THE PH.D. DEGREE

The online publication Qualification Procedure for the Ph.D. Degree describes in detail all requirements in Biomedical Engineering, Chemical and Environmental Engineering, Electrical Engineering, and Mechanical Engineering & Materials Science. The student is strongly encouraged to read it carefully; key requirements are briefly summarized below. See Computer Science’s departmental entry in this bulletin for special requirements for the Ph.D. in Computer Science and the Applied Physics departmental entry for special requirements for the Ph.D. in Applied Physics.

Students plan their course of study in consultation with faculty advisers (the student’s advisory committee). A minimum of ten term courses is required, to be completed in the first two years. Well-prepared students may petition for course waivers based on courses taken in a previous graduate degree program. Similarly, students may place out of certain ENAS courses via an examination prepared by the course instructor. Placing out of the course will not reduce the total number of required courses. Core courses, as identified by each department, should be taken in the first year unless otherwise noted by the department. With the permission of the departmental director of graduate studies (DGS), students may substitute more advanced courses that cover the same topics. During the first year, students are required to register for two Special Investigations; any additional terms of Special Investigations will not count toward
the degree. At least two elective courses must be outside the area of the dissertation. All students must complete a one-term course, Responsible Conduct of Research, in the first year of study.

Each term, the faculty review the overall performance of the student and report their findings to the DGS who, in consultation with the associate dean, determines whether the student may continue toward the Ph.D. degree. By the end of the second term, it is expected that a faculty member has agreed to accept the student as a research assistant, and it is required that by the beginning of the third term, the faculty adviser provides the financial support indicated in the admissions offer letter, barring the award of external funding. By December 5 of the third year, an area examination must be passed and a written prospectus submitted before dissertation research is begun. These events result in the student’s admission to candidacy. Subsequently, the student will report orally each year to the full advisory committee on progress. When the research is nearing completion, but before the thesis writing has commenced, the full advisory committee will advise the student on the thesis plan. A final oral presentation of the dissertation research is required to be given during term time. There is no foreign language requirement.

Teaching experience is regarded as an integral part of the graduate training program at Yale University, and all Engineering graduate students are required to serve as teaching fellows for two terms, typically during year two. Teaching duties normally involve assisting in laboratories or discussion sections and grading papers and are not expected to require more than ten hours per week. Students are not permitted to teach during their first year of study.

If a student was admitted to the program having earned a score of less than 26 on the Speaking Section of the Internet-based TOEFL, the student will be required to take an English as a Second Language (ESL) course each term at Yale until the graduate school’s Oral English Proficiency standard has been met. This must be achieved by the end of the third year for the student to remain in good standing.

CORE COURSE REQUIREMENTS FOR THE PH.D. DEGREE

Applied Physics  See the departmental entry for Applied Physics in this bulletin.

Biomedical Engineering  ENAS 510, ENAS 550. One of these courses may be taken in the second year. In addition, there is a math requirement that must be met by taking ENAS 500, ENAS 505, or ENAS 549 in the first year. Students enrolled in IGPPEB may also meet the math requirement by taking ENAS 541 or ENAS 561.

Chemical and Environmental Engineering (Chemical track)  ENAS 500, and two of the following three courses: ENAS 521, ENAS 602, ENAS 603.

Chemical and Environmental Engineering (Environmental track)  ENAS 640, ENAS 641, ENAS 642. In addition, there is a math requirement that must be met by taking one of the following courses in the first year: ENAS 500, ENAS 748, ENV 758, or S&DS 530. Any other mathematics or statistics class can be taken as an elective in addition to one of these core classes.

Computer Science  See the departmental entry for Computer Science in this bulletin.
Electrical Engineering Courses will be assigned by the adviser in coordination with the research committee, and are subject to approval by the DGS.

Mechanical Engineering and Materials Science Students must demonstrate competence in one of five areas: Fluid and Thermal Sciences, Soft Matter/Complex Fluids, Materials Science, Robotics/Mechatronics, or Bioengineering. As a minimum requirement, students must take at least one of the following courses in the first year of study: CPSC 559, CPSC 570, CPSC 572, CPSC 573, CPSC 585, ENAS 521, ENAS 541, ENAS 559, ENAS 606, ENAS 615, ENAS 703, ENAS 704, ENAS 708, ENAS 752, ENAS 755, ENAS 770, ENAS 773, ENAS 778, ENAS 787, ENAS 848, ENAS 850, ENAS 851, ENAS 902 (if not used to satisfy the math requirement), ENAS 994, PHYS 628. There is a math requirement that must be met by taking CPSC 553, ENAS 500, ENAS 902, or PHYS 506, depending on the research area. In addition, students must take two terms of ENAS 700 during the first two years of study; this course does not count toward the ten-course requirement.

HONORS REQUIREMENT Students must meet the Honors requirement in at least two term courses (excluding Special Investigations) by the end of the second term of full-time study. An extension of one term may be granted at the discretion of the DGS. An average grade of at least High Pass must be maintained through all courses that count toward the Ph.D.

M.D.-PH.D. STUDENTS M.D.-Ph.D. students affiliate with the Department of Biomedical Engineering via the School of Medicine. M.D.-Ph.D. students officially affiliate with Biomedical Engineering after selecting a thesis adviser and consulting with the DGS.

The academic requirements for M.D.-Ph.D. students entering Biomedical Engineering are modified from the normal requirements for Ph.D. students. Other than the modifications listed here, M.D.-Ph.D. students in Biomedical Engineering are subject to all of the same requirements as the other graduate students in the department.

Courses Seven graduate-level courses taken for a grade must be completed during the first two years of the Ph.D. program. (One Yale graduate-level course taken for a grade during medical school may be counted toward this requirement at the discretion of the DGS.) There are three required courses: ENAS 510 and two terms of BENG 990. All students are expected to present their Special Investigation work at a department symposium held on the last day of the reading period. In addition, there is a math requirement, which may be met by taking any one of the following courses: ENAS 500, ENAS 505, or ENAS 549. Among the three electives, one must be in engineering or a closely related field. Students must obtain a grade of Honors in any two of these courses, excluding BENG 990, and maintain an average of at least High Pass.

Teaching Students are required to serve as a teaching fellow for two terms but are not permitted to teach during their first year of graduate study.

Prospectus and qualifying exam M.D.-Ph.D. students must complete and submit their thesis prospectus by the end of the fifth term as an affiliated graduate student. Students who affiliate at the customary point of year three must submit the approved prospectus before the end of the fall term of the fifth year (at the beginning of year three as an affiliated Ph.D. student). After submitting the prospectus, students present their results
to date and their proposed research to their thesis committee in an area examination. Students are given two opportunities to pass this exam.

Candidacy  M.D.-Ph.D. students will be admitted to candidacy once they have completed their course requirements, passed their qualifying exam, and had their dissertation prospectus approved by their advisory committee.

Further requirements  M.D.-Ph.D. students who are admitted to candidacy are required to have an annual Thesis Committee meeting. In the first year after admission to candidacy, students are expected to present their research work at a departmental seminar. Attendance at weekly Biomedical Engineering Seminars is mandatory. A final oral presentation of the dissertation research is required before students may submit to the Dissertation Office.

MASTER’S DEGREES

M.Phil.  See Degree Requirements under Policies and Regulations.

M.S. (en route to the Ph.D.)  To qualify for the M.S., the student must pass eight term courses; no more than two may be Special Investigations. An average grade of at least High Pass is required, with at least one grade of Honors.

Terminal Master’s Degree Program  Students may also be admitted directly to a terminal master’s degree program. The requirements are the same as for the M.S. en route to the Ph.D., although there are no core course requirements for students in this program. This program is normally completed in one year, but a part-time program may be spread over as many as four years. Some courses are available in the evening, to suit the needs of students from local industry.

The Master’s of Science in Personalized Medicine and Applied Engineering  Directed and taught jointly by faculty in the School of Engineering & Applied Sciences and the School of Medicine, this program prepares biomedical, mechanical, and electrical engineers, as well as computer science majors and medical students, with the tools to develop innovative 3D solutions for personalized medicine. The program trains graduate students to develop and apply 3D technology to address surgical and medical conditions, with the goal of personalizing healthcare treatments to improve patient clinical outcomes. Additional societal benefits include lower healthcare costs and improved patient quality of life. Prospective students should apply through the Graduate School of Arts and Sciences (https://gsas.yale.edu/admissions/degree-program-application-process).

The program is one full year: summer through spring. Students are required to participate in an eight-week, summer clinical immersion session prior to registration in fall term sequence courses. Although course credit is not awarded for the clinical program, completion of the requirement will be noted on the transcript.

Students have flexibility in selecting the focus of their special investigation projects as well as an optional biomedical engineering industry collaboration project ("internal internship") tailored to their specific academic backgrounds and interests. For example, students with a strong engineering background may want to focus on medical school-focused classes, while medical students may want to focus on engineering-related courses. Students must take a total of eight courses, of which six courses are required of all students in the program: PMAE 526, PMAE 527, PMAE 528, PMAE 529, and
two terms of PMAE 532 or PMAE 990. In rare exceptions, students may be allowed to take both with approval from the program director and DGS. With the approval of the program’s DGS, the final two courses may be chosen from Yale-wide graduate-level technical electives, which must be approved by the program’s DGS. An average grade of at least High Pass is required, with at least one grade of Honors.

**Joint Master’s Degree Program (School of Engineering & Applied Science and School of the Environment)** The joint master’s degree program offered by the School of the Environment (YSE) and the School of Engineering & Applied Science (SEAS) provides environmental engineers and environmental managers with the opportunity to develop knowledge and tools to address the complex relationship between technology and the environment. This joint-degree program will train graduate students to design and manage engineered and natural systems that address critical societal challenges, while considering the complex technical, economic, and sociopolitical systems relationships. Each joint program leads to the simultaneous award of two graduate professional degrees: either the Master of Environmental Management (M.E.M.) or the Master of Environmental Science (M.E.Sc.) from YSE, and a Master of Science (M.S.) from SEAS. Students can earn the two degrees concurrently in 2.5 years, less time than if they were pursued sequentially. Candidates spend the first year at YSE, the second year at SEAS, and their final term at YSE. Joint-degree students are guided in this process by advisers in both YSE and SEAS. Candidates must submit formal applications to both YSE and SEAS and be admitted separately to each School, i.e., each School makes its decision independently. It is highly recommended that students apply to and enter a joint-degree program from the outset, although it is possible to apply to the second program once matriculated at Yale. Prospective students to the joint-degree program apply to the YSE master’s degree through YSE (https://apply.environment.yale.edu/apply) and to the SEAS master’s degree in Chemical and Environmental Engineering through the Graduate School of Arts and Sciences (https://gsas.yale.edu/admissions/degree-program-application-process).

The following six courses are required of all joint-degree YSE/SEAS master’s students completing their M.S. in Environmental Engineering: ENAS 641, ENAS 642, ENAS 660, ENV 773, ENV 838, and either ENV 712 or ENV 724. Two additional Yale-wide technical electives approved by the DGS (or faculty in an equivalent role in Environmental Engineering) are required. These courses may be cross-listed with or administered by YSE with prior approval from the DGS. For the joint-degree requirements for completion of the M.E.M. or M.E.Sc. in YSE, see the bulletin of the Yale School of the Environment at https://bulletin.yale.edu.

Program information is available via email to engineering@yale.edu or at our website, http://seas.yale.edu.