ABET
Self-Study Report

for the

Chemical Engineering Program

at

Yale University

New Haven, CT

July 31, 2020

CONFIDENTIAL

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for
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Accreditation or Reaccreditation

BACKGROUND INFORMATION

A. Contact Information

Jaehong Kim
Department Chair
Henry P. Becton Sr. Professor of Chemical & Environmental Engineering

Degrees: Ph.D., University of Illinois at Urbana-Champaign

Room / Office: Room 525

Office Address: 17 Hillhouse Ave.
New Haven, CT 06511

Mailing Address: P.O. Box 208263
New Haven, CT 06520

Phone: (203) 432-4386
Fax: (203) 432-4387
Email: jaehong.kim@yale.edu

Michael Loewenberg
Director of Undergraduate Studies
Professor of Chemical & Environmental Engineering

Degrees: Ph.D., California Institute of Technology

Room / Office: Mason Laboratory 303

Office Address: 9 Hillhouse Avenue
New Haven, CT 06511

Mailing Address: P.O. Box 208286
New Haven, CT 06520

Phone: (203) 432-4334
Fax: (203) 432-4387
Email: michael.loewenberg@yale.edu

B. Program History

Instruction in engineering at Yale was given in the Sheffield Scientific School, starting in 1852, making it one of the oldest engineering programs in the United States. In 1936, the Engineers' Council for Professional Development (ECPD – ABET's predecessor) accredited chemical, civil, electrical, mechanical, and metallurgical engineering programs in Yale's School of Engineering. While the civil and metallurgical engineering programs have been suspended, Yale continues to have ABET-accredited programs in chemical, electrical, and mechanical engineering.

To more accurately reflect the growing importance of the Environmental Engineering Program, and to emphasize research and teaching synergies between Chemical and Environmental Engineering at Yale, the "Department of Chemical Engineering" changed its name in 2010 to the "Department of Chemical and Environmental Engineering."

Yale University's Chemical Engineering Program was last reviewed by ABET in 2014.

Major changes to Yale Engineering since 2014:

2015 The Yale Department of Computer Science joins the Yale School of Engineering & Applied Science to increase collaboration and create a closer connection between engineering and computing disciplines. The development includes a commitment to increase the number of Computer Science faculty by seven positions over the next few years.

2016 The School of Engineering & Applied Science (SEAS) completes the 15,000-square-foot renovation of the final two floors (of the former Yale Health building) at 17 Hillhouse to serve as research labs, faculty offices, and student work space for the Department of Chemical and Environmental Engineering. In addition, the building houses the Engineering Librarian as well as consultation and instructional space for library needs. This development marks the conclusion of a six-year process to repurpose and renovate this building.

2017 The Greenberg Engineering Teaching Concourse, composed of eight new undergraduate teaching labs, storage area, and a lab administrative office, opens, co-locating lab instruction for all engineering programs. The new labs have been designed — and are operated — to maximize flexibility in the space, where each lab space can be used to support multiple lab courses. This flexibility increases the utilization rate of the spaces with support systems established to maximize efficiency. Course-specific equipment is provided within the spaces and is stored in adjacent laboratory preparation rooms when not being used.

At the end of the year, Dean Kyle Vanderlick concludes a decade of service to the Yale School of Engineering & Applied Science in many dimensions, including securing a $50 million donation from SEAS alum John Malone to endow 10 new professorships, with this gift being the largest in the School's history. During her deanship, she also created the Yale Center for Engineering Innovation & Design (CEID) and secured the stability of the space with $23 million support from SEAS alum Dr. James S. Tyler. Furthermore, the Greenberg Engineering Teaching Concourse was completed under the leadership of Dean Vanderlick. Finally, she led a university-wide project to renovate the building known as 17 Hillhouse, with the former Yale Health building now serving as a thriving academic and research center on the Yale Engineering campus.

2018 Professor Mitchell Smooke of the Department of Mechanical Engineering & Materials Science is appointed as Interim Dean of the Yale School of Engineering & Applied Science.

The Report of the University Science Strategy Committee, commissioned by Yale's President Peter Salovey, identifies five priority areas for the University to focus on: integrative data science, quantum science, neuroscience, inflammation, and environmental and evolutionary sciences. The report also recommends four cross-cutting investments: graduate student support, diversity throughout the STEM pipeline, instrumentation development, and core facilities. The report emphasizes "the need for Yale to have strength and intellectual coverage in areas of engineering and applied science." Specifically addressing the Yale School of Engineering & Applied Science, the report supports the "Engineering + X strategy for the future of SEAS," with the school having a hub-and-spokes structure across the University.

2019 Dean Jeffrey Brock is appointed to lead the Yale School of Engineering & Applied Science. Dean Brock, the Zhao and Ji Professor of Mathematics and the Dean of Science in the Faculty of Arts and Sciences, will serve as the single leader of Yale's engineering, applied science, and science programs. In that role, Dean Brock leads strategic thinking about the connection across science and engineering. As an internationally recognized data scientist and mathematician, Dean Brock has collaborated in substantial research partnerships with computer scientists. As Yale's leader of science and engineering, he will help implement Yale's strategy for these disciplines as established in the Report of the University Science Strategy Committee.

Construction begins on the Tsai Center for Innovative Thinking at Yale (Tsai CITY), a 12,500-square-foot building adjoining the CEID. Under the supervision of Yale's Provost, the new center will support students from diverse backgrounds and disciplines seek innovative ways to address real-world problems. As described by Yale's President Salovey, the CEID, the Greenberg Engineering Teaching Concourse, and Tsai CITY establish Yale's Innovation Corridor as a new model to catalyze innovation, creativity, and discovery.

2020 Provost Scott Strobel is appointed as Yale's Provost, replacing Professor Ben Polak who served as Yale's Provost from 2012 to 2019. Provost Strobel, the Henry Ford II Professor of Molecular Biophysics and Biochemistry, had previously chaired the University Science Strategy Committee, led the development of Yale's Poorvu Center for Teaching and Learning, and was Yale's Vice President for West Campus Planning and Program Development where he guided all aspects of a remote 136-acre site for research and learning.

The Yale Department of Applied Physics joins the Yale School of Engineering & Applied Science. Among other benefits, the inclusion of Applied Physics within the School of Engineering & Applied Science facilitates collaboration regarding quantum science, which was one of the priorities in the Report of the University Science Strategy Committee.

Major changes to Yale Chemical Engineering since 2014:

Changes to Program Faculty:

Professors Wilson (2016), Taylor (2017), and Osuji (2018) left, and Professor Haller retired (2015). Four new Program Faculty were hired: Professors Hu (2016), Zhong (2016), Haji-Akbari (2017), and Guo (2020). Professor Zhong was reappointed as an assistant professor (2020).

Changes to the Program:

- A new teaching lab was built.
- Two core courses were introduced.
- Two revisions were made to Program requirements.
- A new set of Program Educational Objectives was adopted.

C. Options

The Program offers an ABET-accredited B.S. degree in Chemical Engineering, and a non-ABET B.S. in Engineering Sciences (Chemical).

Accreditation is sought only for the B.S. in Chemical Engineering.

D. Program Delivery Modes

The Program offers only a traditional daytime, lecture/laboratory based curricular delivery mode.

E. Program Locations

The Program is offered at the main campus of Yale University in New Haven, CT.

F. Deficiencies, Weaknesses, or Concerns from Previous Evaluation(s) and the Actions Taken to Address Them

The 2014 ABET Final Statement identified "Criterion 6: Students" as a concern. The statement included the following:

> "Criterion 6. Faculty: This criterion requires that the faculty must be of sufficient number and must have the competencies to cover all of the curricular areas of the program.

> Chemical phase equilibria, normally taught in CENG 300, Chemical Engineering Thermodynamics, is central to chemical engineering education. Currently the program's students have been taking a mechanical engineering thermodynamics course (MENG 211), and the course has been co-taught to ensure adequate coverage of phase equilibria. Use of the mechanical engineering course with added content was necessary due to the program's decision to use ladder faculty to teach core chemical engineering courses, the institution's liberal leave policy, and the small number of program faculty available to teach the core courses. Although the program currently satisfies the criterion, the potential exists that this criterion may not be satisfied in the future."

The program did not provide a response to this shortcoming during the due process period, and it remained unresolved in the 2014 ABET Final Statement.

In response to this concern and other factors, the Department has taught CENG 300, Chemical Engineering Thermodynamics, each fall since 2015 with this course taught by chemical engineering ladder faculty (Prof. Osuji: 2015; Prof. Hu: 2016, 2017, 2018; Prof. Vanderlick: 2019).

The 2014 ABET Final Statement identified "Criterion 7: Facilities" as a concern. The statement included the following:

> "<u>Criterion 7. Facilities:</u> This criterion requires that the classrooms, offices, laboratories, and associated equipment be adequate to support attainment of the student outcomes and to provide an atmosphere conducive to learning. CENG 412L, Chemical Engineering Lab, is used to reinforce concepts previously taught in lecture-based courses. Currently the unit operations laboratory used three experiments that reinforced heat transfer (CENG 315), separation and purification (CENG 411), and chemical reaction kinetics (CENG 301). The existing laboratory does not appear to have sufficient resources to support additional experiments. The program augments this teaching laboratory by conducting additional experiments in research facilities. While research laboratories can accommodate the current small class sizes, any future enrollment growth may limit the program's ability to offer some laboratory experiences. Thus, there is potential that this criterion might not be satisfied in the future."

The program did not provide a response to this shortcoming during the due process period, and it remained unresolved in the 2014 ABET Final Statement.

In response to this concern and other factors, the Yale School of Engineering & Applied Sciences opened the Linda and Glenn H. Greenberg Engineering Teaching Concourse in Fall 2017. This 10,000 square foot teaching lab space consists of eight separate labs, including two wet labs with ventilation hoods and a tissue culture rooms, as well as storage rooms and an office to the lab's staff. The new labs were funded with a $10 million donation and are used by all disciplines within the School of Engineering & Applied Science under the direction of the Dean's Office. The facility was created for the sole purpose of improving the undergraduate education experience for Yale's engineering students.

CENG 412L is now held in the Greenberg Engineering Teaching Concourse. In addition to the previous equipment dedicated to CENG 412L, Chemical Engineering Laboratory and Design, the following equipment has been purchased to be used within the course: Dynamic Light Scattering Device (for particle/protein sizing/analyzing) (2015), Continuous Distillation Unit (2017), Heat Transfer Experiment (2018), and Continuous Reactors Study Unit (2019). The equipment is housed in the wet labs within the Greenberg Engineering Teaching Concourse.

The 2014 ABET Final Statement identified "Program Criteria" as a concern. The statement included the following:

> "Program Criteria: The program criteria for chemical, biomedical, biomolecular and similarly named engineering programs requires that the curriculum include the engineering application of basic sciences to the design, analysis, and control of chemical, physical, and/or biological processes, including the hazards associated with these processes. Although evidence was provided to illustrate that safety was emphasized in the unit operations laboratory course (CENG 412L), limited evidence was available to confirm that process safety was covered in other parts of the curriculum. While the program currently satisfies the criterion, the potential exists that changes to the unit operations laboratory course may cause the emphasis on process safety to be lost. There is therefore a risk that future compliance with this criterion may be jeopardized."

The program did not provide a response to this shortcoming during the due process period, and it remained unresolved in the 2014 ABET Final Statement.

In response to this concern, the emphasis on safety has remained in CENG 412L, Chemical Engineering Laboratory and Design, with additional attention given to this subject area with the opening of the new labs and the addition of new experiments. Specific attention to safety will be highlighted in the CENG 412L course documentation. The Yale Office of Environmental Health and Safety guides all aspects of lab safety at Yale, including routine inspections of labs and equipment and university-wide lab safety training. The School of Engineering & Applied Science has an EHS professional (Dr. Shumin Bian) dedicated to the School's facilities, and the Greenberg Engineering Teaching Concourse is regularly inspected and monitored by the EHS professional. In addition to these efforts, a Ph.D. research scientist has been employed (part-time level of effort) in the Greenberg Engineering Teaching Concourse to assist with all aspects, including safety, of Chemical Engineering labs.

CRITERION 1. STUDENTS

A. Student Admissions.

All students admitted to Yale College are free to select any program of study, including engineering. Each year, the Yale College Admissions Office examines approximately 38,000 applications to form a class of 1,500 students. (See Table 1-1 below.) Admissions looks for academic ability and achievement combined with such strengths as motivation, curiosity, energy, and leadership ability. No simple profile of grades, scores and activities guarantee admission. In recent years, over 400 students expressing an interest in engineering have been admitted, and slightly over half matriculate to yield approximately 250 First-Year students interested in engineering. First-Years are regularly admitted with advanced standing in a few subjects including Chemistry, English, Mathematics, and Physics. Such students usually start with advanced courses in these subjects, and often take introductory engineering courses in their first year. First-Years interested in engineering are strongly encouraged to take engineering prerequisite courses in their first year.

Table 1-1. Number of new students enrolled in Yale College over the past five years and their corresponding test scores.

Academic Year	Middle 50% ACT		Middle 50% SAT		% of Students in Top 10%	Number of New Students Enrolled
	25%	75%	25%	75%		
2015–2016	31	35	710	800	95%	1,364
2016–2017	32	35	710	800	95%	1,373
2017–2018	32	35	710	800	96%	1,580
2018–2019	33	35	720	790	95%	1,578
2019–2020	33	35	720	790	92%	1,554

B. Evaluating Student Performance

Student compliance with Program curricular requirements is monitored through student course registration forms that are approved each semester by the Program Director of Undergraduate Studies (DUS). Student transcripts provide a running record of each student's progress toward the Chemical Engineering degree; they are maintained online by the registrar and are available to the DUS. (Student transcripts for the graduating classes of 2019 and 2020 will be available during the virtual site review.)

Any substitution for a required course, and all engineering electives, must be approved by the DUS. Justification for non-standard substitutions are recorded and kept on file in students' folders.

At the beginning of each semester, the DUS reviews each student's transcript and proposed course schedule to ensure that the student has taken the course prerequisites and that the proposed courses keep the student on schedule to complete the requirements for the degree by the end of their senior year. If any prerequisite courses are missing, the DUS discusses the matter with the student, and advises of the possibility to obtain an exemption from the course instructor. If there is any doubt about the student's ability to complete the requirements on time, the DUS helps the student to come up with a contingency plan that would typically include taking 1–2 courses in summer session.

Students in Yale College can transfer up to two courses from a four-year accredited university within the US. In the case of transferring courses required for the major, course syllabi are reviewed by the DUS, who then consults with colleagues (often the instructor of record for the equivalent Yale course) to determine the appropriateness of accepting the substitution. Course substitutions from study abroad, are similarly handled. In addition, courses taken as part of an international studies program are reviewed by Yale College, who determines separately whether to count the course toward the Yale degree.

Some additional information on substitutions for required courses is provided here. Standard substitutions include the organic chemistry sequence CHEM 174/175 for CHEM 220/221 because they cover the same material, computer science courses CPSC 100, 112 (or a more advanced computer science course) can be substituted for ENAS 130 because that course content exceeds the computational coverage provided in ENAS 130. These substitutions are noted in all of our curriculum documentation (online at http://seas.yale.edu/departments/chemical-and-environmental-engineering/undergraduate-study-chemical/undergraduate-curric, School of Engineering & Applied Science View Book, Yale College Programs of Study Catalog). Nonstandard substitutions are documented.

Three engineering electives are required for the ABET Chemical Engineering degree. These are subject to DUS approval. Below is a list of typical (acceptable) elective courses.

- CENG 351: Biotransport and Kinetics
- CENG 373: Air Pollution Control
- CENG 377: Water Quality Control
- CENG 471: Independent Research
- CENG 473: Air Quality and Energy
- ENVE 360: Green Engineering
- MENG 280: Mechanical Engineering I: Strength and Deformation of Mechanical Elements
- MENG 285: Introduction to Materials Science
- MENG 365: Chemical Propulsion Systems

- MENG 383: Mechanical Engineering III: Dynamics
- MENG 440: Applied Numerical Methods for Algebraic Systems, Eigensystems, and Function Approximation
- MENG 441: Applied Numerical Methods for Differential Equations
- EENG 310: Signals and Systems
- EENG 320: Introduction to Semiconductor Devices
- EENG 410: Physics and Devices of Optical Communication
- EENG 406: Photovoltaic Energy
- EENG 428: Sensors and Biosensors
- BENG 249: Introduction to Biomedical Computation
- BENG 350: Physiological Systems
- BENG 352: Biomedical Signals and Images
- BENG 353: Introduction to Biomechanics
- BENG 434: Biomaterials

Fractional engineering content for courses taught in science departments may be counted on a case-by-case basis. The DUS has authority to grant fractional credit, and in cases of uncertainty, consults beforehand with other faculty members. Such requests are very rare.

Additionally, students often do independent research projects (CENG 471) for an ABET Chemical Engineering elective, working in a professor's lab on an engineering topic.

C. Transfer Students and Transfer Courses

Yale College welcomes a small number of transfer students, each year (typically between 20 and 30 each year). Transfer students enter either the sophomore or junior year, and must enroll at Yale for a minimum of two years (four terms) to qualify for a bachelor's degree. Students may transfer from fully accredited two- or four-year institutions.

Table 1-3: Number of transfer students enrolled in Yale College

Academic Year	Number of Transfer Students Enrolled	Number of SEAS Majors
2015–2016	24	0
2016–2017	24	0
2017–2018	26	1 (Chemical Engineering)
2018–2019	16	1 (Environmental Engineering)
2019–2020	21	0

As competitive as the admissions process is for First-Year students, the transfer process is even more so. Yale receives more than 1,000 transfer applications each year, and we have space for only 20 to 30 students. While GPA is not the only factor that the admissions committee takes into consideration, it may be helpful to note that the average college GPA of admitted transfer candidates is 3.9. Admission is determined following review by the Yale College Admissions Office.

The following regulations apply to students admitted to Yale College by transfer from other institutions:

1. To graduate from Yale College, transfer students must fulfill all the requirements for the bachelor's degree. They must thus earn a total of the equivalent of at least thirty-six course credits that total consisting of the sum of the credits awarded to them for their work at their previous institutions with course credits subsequently earned at Yale. They must also complete the requirements of a major program in Yale College and fulfill the distributional requirements for the bachelor's degree, which includes the foreign language requirement.

2. Transfer students are expected to enroll in Yale College for the number of terms designated at the time of the final credit evaluation made of their work at previous institutions. Under no circumstances may a transfer student complete less than four terms of enrollment in Yale College. Under no circumstances may a transfer student earns fewer than eighteen course credits at Yale or accelerate by use of acceleration credits.

3. A preliminary evaluation of transferable credits is made at the time of the student's admission. Final evaluation of transfer credits is completed when all official transcripts from a student's previous institutions have been received.

4. A transfer student's Yale transcript indicates the institution from which the student transferred to Yale, and the number of course credits earned there. It does not list the titles of courses taken or grades earned at the transfer student's previous college or university.

5. Transfer students may receive course credit for work completed outside Yale only for studies completed before matriculation at Yale; transfer students may not receive course credit for any outside courses taken after they have enrolled in Yale College.

One student transferred into the Program during the 2014–2020 ABET cycle.

Credit transfer is evaluated both by Yale College with respect to Yale’s graduation requirements and by the Chemical Engineering DUS with respect to program requirements. Regarding Yale College, a student may apply as many as two course credits earned at another college or university toward the 36-course-credit requirement for graduation from Yale. Credits earned outside Yale may not be used to reduce the expected number of terms of enrollment in Yale College.

For credit to be given for courses taken elsewhere, all of the following conditions must be met:

1. The Director of Undergraduate Studies in the subject of a course taken elsewhere must approve the award of credit at Yale for the course.

2. A student who has studied at an American university, or abroad on a program sponsored by an American university, must provide the office of the residential college dean with an official transcript of the work completed. A student who has enrolled at a foreign university should supply an official transcript if the university issues transcripts; if it does not, then the student must furnish an official certificate of enrollment, showing if possible the course or courses completed.

3. Students seeking outside credit should be prepared to furnish a copy of the course syllabus, as well as essays and examinations written in the course. In some cases, a letter from the instructor of the course may be required, or the student may be asked to pass an examination on the material of the course. Such information may be particularly necessary in the case of study at a foreign university.

4. Study undertaken in the United States must be at a four-year accredited institution that grants a bachelor's degree in the arts and sciences. Foreign study must be completed at a university or other approved institution. Credit may be awarded only for work done while a student was officially enrolled in such an institution, and cannot be given for any work completed independently of such formal enrollment.

5. A grade of A or B is expected; a grade of C is acceptable. Credit cannot be given for a course in which a grade of D was earned. Credit also cannot be given for a mark of Credit on a Credit/D/Fail option, nor for a grade of Pass on a Pass/Fail option, if the student had the choice of taking the course for a letter grade.

6. In order for credit to be given for a course completed at another university, the course must carry a value of at least three semester credit hours; if the course is taken at an institution on the quarter system, it must carry a value of at least four-and-one-half quarter units.

7. In order for credit to be given for a course completed at another university, the number of contact hours for the course must equal or exceed the number of contact hours for an equivalent course offered in Yale College during the fall or spring term, and the length of term (from the first to the last day of classes) must be at least four consecutive weeks.

Regarding program requirements in Chemical Engineering, the transferring student petitions the Program DUS to accept any credits approved by Yale College (see above) toward specific course requirements of the major. As in the case of substitutions, the DUS often consults with colleagues, including the instructor of record for the equivalent Yale course, to determine the appropriateness of accepting a given course as a transfer credit.

D. Advising and Career Guidance

Yale students receive career and academic guidance from a few individuals. This "constellation of advisers" helps students navigate the academic and other developmental aspects of life in Yale College.

Each undergraduate program at Yale is advised by a Director of Undergraduate Studies (DUS). Directors of Undergraduate Studies are authorities on the nature and objectives of their disciplines and the general features of the undergraduate program. More particularly, the DUS is familiar with the range, focus, and objectives of individual courses of the program, as well as with placement policies and major requirements. Prof. Michael Loewenberg currently serves as the Program DUS.

The DUS meets with students at least once per semester, to review academic progress and the student's proposed course selection for the following semester. In many cases, these meetings also cover topics such as undergraduate research opportunities, extracurricular activities (including the Yale Chapter of the AIChE), and/or career opportunities. Many students meet with the DUS multiple times each semester.

While the DUS has primary responsibility for each student's progress, a host of other advisers also assists Yale undergraduates. Much of this additional guidance is organized around the Residential Colleges, where students reside during their four years at Yale.

The First-Year Counselor is a senior who lives with First-Years and serves as a source of information and assistance throughout the year, especially in the early weeks of the fall term. A small number of students are assigned to each First-Year Counselor, who gives suggestions about curricular and extracurricular options and is readily available to take an interest in students' academic or personal concerns. As seniors in Yale College, they can often give firsthand advice on how best to use the facilities, both academic and social, of the Residential Colleges and of Yale College.

A fellow of a Residential College, either a member of the faculty or a fellow knowledgeable about education in Yale College, acts as the First-Year Faculty Adviser. During the course selection period, First-Years meet with their advisers both to discuss the broad outline of their academic career and to approve the specific courses they choose for the year. No First-Year Faculty Adviser can be expected to know everything about the curriculum, but any adviser can put a student in touch with someone who can answer a question that he or she cannot. And as a faculty contact, the adviser can also help throughout the school year with educational plans. Students are encouraged to discuss with their adviser not only their choices of particular courses, but also the relative merits of various options in the Yale curriculum. The signature of the faculty adviser on course schedules comes after a careful discussion of the student's course of study.

The Residential College Dean plays a central role in undergraduates' academic careers. As the representative of the Yale College Dean's Office in the Residential College, the Residential College Dean administers the academic regulations and oversees First-Year Counseling and Faculty Advising. The dean also counsels' students on personal and academic matters and gives advice about the rules of Yale College. The Residential College Dean's office maintains students' academic records. For these reasons and others, the Dean is crucial to academic life at Yale.

Finally, undergraduate students also have access to the opportunities provided by the Office of Career Strategy (OCS). The Office of Career Strategy offers career counseling, professional school advising, employment and internship opportunities, and career development resources. The Yale OCS works with undergraduates to clarify career aspirations, identify employment and educational opportunities, and offer counseling and support at every stage of career development. David Halek is the Director of Employer Relations of OCS who oversees the OCS team that advises students interested in engineering careers. As an example of his effectiveness, Mr. Halek organizes a series of discipline-based networking events where students interact with visiting professionals and pursue employment opportunities.

E. Work in Lieu of Courses

Yale College does not award credit for work in lieu of courses.

F. Graduation Requirements

Each student must complete 36 term courses, or their equivalent, within Yale College. In doing so, the student must fulfill the distributional requirements of Yale College and the requirements of a major program. These requirements are clearly stated in the "Yale College Programs of Study," which is published annually.

The requirements for the Bachelor of Science degree in Chemical Engineering are as follows:

Prerequisites: Students take the following prerequisite courses: MATH 112, 115, and ENAS 151 or equivalent; PHYS 180, 181, or a more advanced sequence; CHEM 161, 165, and 134L, 136L, or a more advanced sequence. Students with advanced high school preparation may reduce the number of prerequisites.

Required courses:

1. Mathematics: ENAS 194 or equivalent

2. Chemistry: CHEM 220, 221 or CHEM 174, 175 and 221L, 223L; CHEM 332, 333

3. Computing: ENAS 130 or CPSC 100 or CPSC 114

4. Engineering: MENG 361. Starting next year 2021, this course will be replaced by CENG 314.

5. Three engineering electives (subject to DUS approval)

6. Chemical engineering: CENG 150, 300, 301, 315, 411, 412L, 480

7. Capstone design: CENG 416, Chemical Engineering Process Design.

Each semester, the DUS confirms that student transcripts are consistent with completion of the program by the end of the student's senior year. Just prior to graduation, the DUS submits a checklist, for each student, to the Yale College Registrar, indicating that all program requirements have been met. The Registrar's Office completes a similar checklist, indicating that all other Yale College graduation requirements have been met.

G. Transcripts of Recent Graduates

Transcripts of recent Program Graduates are available for viewing and will be forwarded separately to the ABET Team Chair.

CRITERION 2. PROGRAM EDUCATIONAL OBJECTIVES

A. Mission Statement

Yale's primary mission is to attract, educate and motivate a diverse group of the most highly talented men and women in order to advance and disseminate knowledge and to promote the scholarship, high character, values, and leadership which can be directed towards sustaining and improving society. Intrinsic to this mission are the faculty's dual responsibilities for outstanding teaching and original research, carried out in a community comprised of Yale College, a Graduate School with broad coverage of the arts and sciences, and an array of professional schools in arts, sciences, and learned professions. This mission requires a continuing commitment to the excellence, the competitive position, and the reputation for academic leadership that Yale has earned over three centuries.

B. Program Educational Objectives

Yale University's Chemical Engineering Program Educational Objectives (PEOs) are listed below.

Graduates from the Yale Undergraduate Chemical Engineering Program will:

1. Have mastery of the basic principles of science and modern chemical engineering practice and be able to adapt and creatively apply them to solve new problems in a broad range of fields.
2. Become ethical professionals who advance chemical engineering practice and knowledge in multiple fields and recognize the local and global impacts of their work on humans and the environment.
3. Be able to work well with people from diverse backgrounds and be committed to the advancement of women and under-represented groups in engineering.
4. Have strong educational foundation enabling them to study in graduate and professional schools as well as become leaders in STEM or non-STEM career paths.
5. Be committed to, and engage in, lifelong learning throughout their careers.

The above PEOs are new. They were created through consultation with the Program Constituencies (see Section D below) during the present self-study. This involved discussions with current students, surveys of recent graduates, and a series of meetings and discussions with the Yale Science & Engineering Association. Finally, the PEOs were approved by the Program Faculty. The Program Educational Objectives are posted on the Department's web site.[1]

[1] See http://seas.yale.edu/departments/chemical-and-environmental-engineering/undergraduate-study-chemical.

For reference in the discussion that follows below, the former PEOs are given here.
Graduates from the Yale Undergraduate Chemical Engineering Program will:

1. Achieve positions of leadership within academia, industry, government, and the non-profit sector.
2. Enter and excel within top graduate programs in chemical, biomedical, environmental, and related engineering fields.
3. Enter and excel within top professional schools e.g. law, medicine, or management.
4. Enter and rise within large and small corporations.
5. Become successful entrepreneurs.
6. Practice engineering toward the benefit of humankind.

There is clearly overlap between the new and former PEOs: the new PEO 2 essentially covers the former PEOs 1 and 6 and the new PEO 4 essentially covers the former PEOs 2 and 3. The new PEOs 1 and 2 imply the former PEOs 4 and 5 though not explicitly. On the other hand, the thrust of the new PEOs 3 and 5 are absent from the old set of PEOs. The motivation for a complete overhaul of our PEOs stemmed from the lack of PEOs that addressed the need to work with people from diverse backgrounds, the importance of a broader participation within engineering, the need for adaptive lifelong learning, and a sense that the number of PEOs should be limited.

C. Consistency of the Program Educational Objectives with the Mission of the Institution

The Program Educational Objectives speak to graduates being equipped for a broad range of professions, having the tools to adapt to a rapidly evolving workplace, and becoming ethical leaders who consider the effects of their actions on all people and the environment. Yale's mission to "educate and motivate a diverse group of the most highly talented men and women" and "advance and disseminate knowledge and to promote the scholarship, high character, values, and leadership" is entirely consistent with our new PEOs.

D. Program Constituencies

Yale's Chemical Engineering Program considers as its key constituencies i) current students majoring in chemical engineering, ii) Yale alumni with chemical engineering degrees, and iii) the Yale Science and Engineering Association. The PEOs are designed to meet the needs of these constituencies as follows:

- <u>Current chemical engineering students</u> seek to obtain employment, or to enter graduate or professional programs, following their graduation from Yale. Ultimately, they seek to advance within their chosen professional path. The PEOs are very much in line with these student needs.

- Chemical engineering alumni wish to see the Program thrive and continue to improve, and in addition occasionally seek to employ more recent graduates. The PEOs are very much in line with these alumni needs.

- Yale Science and Engineering Association (YSEA), is an alumni group dedicated to science and engineering excellence at Yale. The organization provides financial and programmatic support for recruiting, retaining and educating science and engineering students at Yale. This group is often consulted for feedback as the members have a personal interest in improving Yale's science and engineering programs, and collectively represent a diverse field of industries and professional disciplines. The YSEA Advisory Committee is a small group that interacts regularly with the Yale School of Engineering and Applied Science and is available for consultation by Yale SEAS Departments. By meeting its PEOs, the Program is achieving an excellent standard of educating its undergraduate students, and thus meets the needs of this constituency.

E. Process for Review of the Program Educational Objectives

Assessment of the degree to which the PEOs meet the needs of the Program constituencies occurs via input from Program Alumni, graduating seniors, and The Yale Science and Engineering Association. The process is summarized in Table 2-1 and described in more detail in the text below.

Table 2-1. The Yale Chemical Engineering Program Educational Objectives Review Process.

Group	Frequency	Format
Program Alumni	Every three years	E-mailed survey
Graduating Seniors	Every year	Exit interview
Yale Science and Engineering Association	Every three years	Meeting agenda & survey

Surveys of Program Seniors and Alumni

Surveys are administered every three years to alumni. Responses are sought for each PEO on a scale of 0 (does not meet the needs of the Program Constituency) to 5 (successfully meets the needs of the Program Constituency). Respondents may also add written material. These assessments provide a clear indication of the degree to which the PEOs meet the needs of these constituencies. The results of past surveys for the former PEOs shown in Table 2-2 indicate that our PEOs have been reasonably serving the needs of our students.

Senior exit interviews

The Program Director of Undergraduate Studies (DUS) conducts exit interviews of the graduating seniors each year. The DUS reports on the results of the exit interviews at a faculty meeting, and based on these reports and the ensuing discussions, revisions to the PEOs (and other corresponding aspects of the Program) may be proposed.

Yale Science and Engineering Association (YSEA) feedback

A representative group from the YSEA meets periodically with the Chemical Engineering DUS and discusses various aspects of the Program, including the degree to which the PEOs meet the needs of the Program constituencies. The YSEA group is a highly engaged group of alumni from our Program and other engineering departments at Yale. As discussed below, their involvement was critically important this year.

Table 2-2: Survey Results: Former Program Educational Objectives.

Results of alumni and senior class surveys on the degree to which the former PEOs address the students' educational needs (0 = lowest, 5 = highest).

PEO	Alumni 2015	Seniors 2015	Seniors 2018
1	3.8	3.2	3.5
2	4.0	4.1	3.9
3	4.5	4.2	4.5
4	3.5	3.3	3.6
5	3.1	3.6	3.3
6	4.2	4.0	4.2
Average	3.85	3.73	3.83

Occasional Overhaul of Program Educational Objectives

The above process of incrementally revising our PEOs provides an adaptive mechanism for revising our PEOs. An "optimal" set of PEOs can be defined as the best fit to our students' needs as measured by survey data, subject to the constraint that the PEOs are compatible with the ABET Student Outcomes (Chapter 3). A simple measure that could be optimized is the average PEO score (1-5). By this measure, the results shown in the bottom line of Table 2-2, indicate that while our former PEOs were a reasonable fit to our students' needs, they were not being effectively optimized. It makes sense that an optimal set of PEOs may not necessarily be rapidly obtained by incremental revision.

Noting the lack of optimization evident in Table 2-2, the PEOs were completely reformulated during the 2019–2020 AY rather than incrementally revised. This was driven by Yale alumni from the YSEA. The new PEOs listed above were developed through a series of meetings and group email exchanges with approximately 10 YSEA members over several months. The new PEOs were approved by the chemical engineering faculty. They are strongly supported by our most recent graduating class as shown by the data in Table 2-3.

Table 2-3: Survey Results: New Program Educational Objectives

Results of alumni and senior class surveys on the degree to which the new PEOs address the students' educational needs (0 = lowest, 5 = highest).

PEO	Alumni 2020 & Seniors 2021
1	4.9
2	4.7
3	4.6
4	4.6
5	4.6
Average	4.69

Summary of PEO review process

This section detailed how the specific constituencies — students, alumni, and a professional society — are involved in a periodic review process to determine the extent to which the PEOs address their needs and suggest revisions. A weakness of this approach is inefficient optimization. Accordingly, it is helpful to completely reevaluate the PEOs every several years to adapt to changes the target workplaces for our students and societal needs.

CRITERION 3. STUDENT OUTCOMES

A. Student Outcomes

The Yale University Chemical Engineering Program adopts the ABET 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 a team 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 Student Outcomes are documented on the Department's web site.[1]

B. Relationship of Student Outcomes to Program Educational Objectives

The Chemical Engineering curriculum is designed to meet the Program's Educational Objectives. Table 3.1 below shows the relationship between the Program Educational Objectives and the Student Outcomes. As seen in Chapter 2 of this Self-Study Report, the Program Educational Objectives for the Chemical Engineering Department are:

1. Have mastery of the basic principles of science and modern chemical engineering practice and be able to adapt and creatively apply them to solve new problems in a broad range of fields
2. Become ethical professionals who advance chemical engineering practice and knowledge in multiple fields and recognize the local and global impacts of their work on humans and the environment
3. Be able to work well with people from diverse backgrounds and be committed to the advancement of women and under-represented groups in engineering

[1] See http://seas.yale.edu/departments/chemical-and-environmental-engineering/undergraduate-study-chemical.

4. Have a strong educational foundation enabling them to study in graduate and professional schools as well as become leaders in STEM or non-STEM career paths
5. Be committed to, and engage in, lifelong learning throughout their careers

Table 3-1. Indication of Student Outcomes (columns) contributing to Program Educational Objectives (rows).

PEO	1	2	3	4	5	6	7
PEO 1	X	X				X	X
PEO 2	X	X		X	X	X	X
PEO 3			X	X	X		
PEO 4	X	X				X	X
PEO 5			X	X		X	X

Clearly, many of the Student Outcomes contribute to meeting all or most of the PEOs. For example, since engineering experimentation, analysis, drawing conclusions, and learning new techniques are all activities that are fundamental to the training and work of an engineer, SOs 6 and 7 contribute to nearly all of the PEOs. Similarly, each PEO is addressed by several of the SOs.

As noted by this matrix, attaining the Student Outcomes infers that the students are prepared to attain the PEOs. Note that no single PEO is dependent on a single Student Outcome; instead the relationship is resilient and assures PEO preparation from multiple Student Outcomes.

CRITERION 4. CONTINUOUS IMPROVEMENT

A. Student Outcomes

The Yale Chemical Engineering Program uses a variety of assessment processes to determine the extent to which Student Outcomes are attained. The Program's portfolio of assessment methods include:

1. Course-based Student Outcomes assessment (direct assessment)
2. Faculty reviews of capstone design course (direct assessment)
3. Biannual individual meetings with students (indirect assessment)
4. Anonymous surveys of students (indirect assessment)
5. Exit interviews of graduating seniors (indirect assessment)
6. Annual anonymous surveys of recent graduates (indirect assessment)

Data from each assessment method are gathered and retained by the DUS as a component of the DUS records. The Program DUS, Chair, and Faculty use the results of the assessment methods to evaluate the degree to which the Student Outcomes are attained across the Program. Each of these processes is described below.

1. Course-based Student Outcomes assessment

Our course-based Student Outcomes assessment is embedded within each course. This method — known as the "Yale Method" — was first used during the 2008 ABET General Review process to measure the attainment of Student Outcomes for Yale's Mechanical Engineering Program. The method was adopted by all of the Yale's ABET-accredited programs for the 2014 accreditation cycle and is used for the current accreditation cycle. The method was also shared with the larger academic community as a component of an ASEE paper/presentation at the 2014 Annual Conference.

(i) Overview of course-based Student Outcomes assessment:

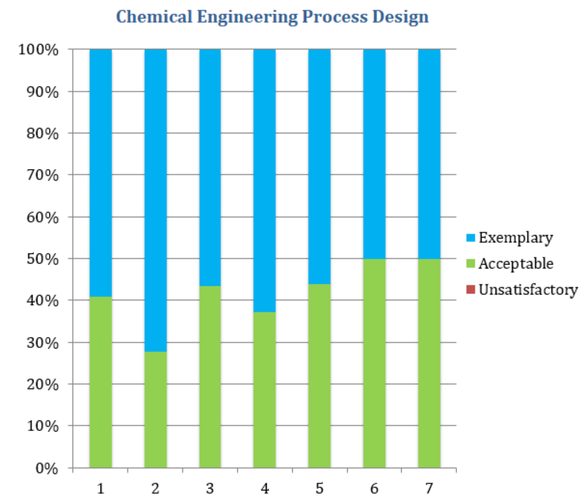
An overview of our course-based assessment tool is provided here; the details follow. Faculty members in core Chemical Engineering courses enter their normal grading assessments on a standard Excel spreadsheet. The grades and weights for all student work (problem sets, lab reports, exams, and projects) are entered in a table. To compensate for scoring differences between instructors, the course instructors enter scores corresponding to unsatisfactory, acceptable and exemplary levels of performance. The key aspect of this assessment method is a course assessment matrix completed by each instructor that maps all items of coursework onto Student Outcomes; an example is shown in Figure 4-1. Note that the different items of coursework have relevance to different SOs, and frequently a single item covers multiple SOs.

ABET Outcome	PS1	PS2	PS3	PS4	HYSYS Lab 1	HYSYS Lab 2	HYSYS Lab 3	Mid-Term Exam	Capstone Project	Course
1		0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.10	19.6%
2	0.50	0.40	0.40	0.40					0.10	10.0%
3					0.40	0.40	0.40	0.15	0.10	13.7%
4	0.50	0.30	0.30	0.30					0.25	14.4%
5					0.30	0.30	0.30		0.20	10.7%
6								0.25	0.10	13.0%
7								0.35	0.15	18.5%
(should sum to 1)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	100.0%

Figure 4-1. Example course assessment matrix (from CENG 416) that relates coursework to relevant Student Outcomes.

Results: Course Summary for CENG 416 / ENVE 416 (Spring 2020)

*If the chart does not appear, please select the tabular data on the right of the chart and insert your own column chart.



Outcome	Unsatisfactory	Acceptable	Exemplary	Total
1	0%	41%	59%	100%
2	0%	28%	72%	100%
3	0%	44%	56%	100%
4	0%	37%	63%	100%
5	0%	44%	56%	100%
6	0%	50%	50%	100%
7	0%	50%	50%	100%

Note that 1-7 items not evaluated (i.e., no entries in the matrix) do not have a column in the graph.

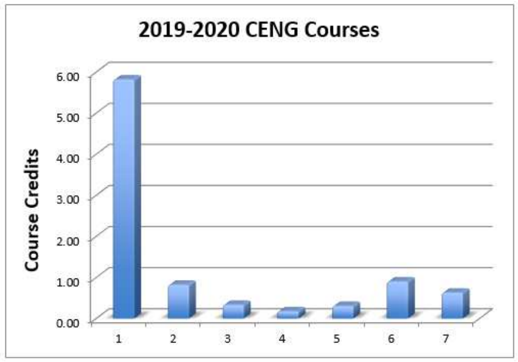
Figure 4-2. Student Outcomes assessment summary for Chemical Engineering Process Design (CENG 416), Spring 2020.

Only the course work grades, cut-off scores for satisfactory and exemplary performance, and a course assessment matrix are required from each instructor. The summary performance of the students in a course is automatically computed by the spreadsheet; an example is shown in Figure 4-2. Instructions for using this system, including templates for the coursework grades and course assessment matrix, are provided to instructors at the beginning of the semester, and the data is collected at the end of the term. The simplicity of the process allows a large number of faculty members to be involved in the assessment process.

An important feature of our course-based SOs assessment method is the ease with which the data is aggregated to provide an assessment of SOs for the entire Program: (i) the relative weights (i.e., distribution of credits) that the Program places on each Student Outcome, shown in Figure 4-3, and (ii) the overall attainment of Student Outcomes, shown in Figure 4-4.

YALE SCHOOL OF ENGINEERING AND APPLIED SCIENCE

CHEMICAL ENGINEERING ABET OUTCOME REVIEW

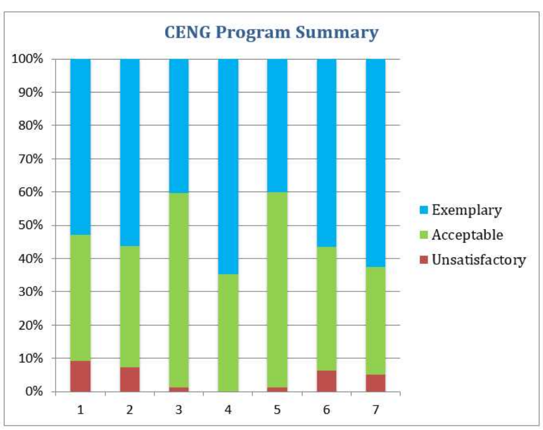


Outcomes	CENG 150	CENG 300	CENG 301	CENG 315	CENG 411	CENG 412	CENG 416	CENG 480	MENG 361	Total Course Credits
1	80.9%	85.0%	83.5%	64.0%	98.4%	0.0%	19.6%	50.5%	100.0%	5.82
2	14.1%	5.7%	15.5%	16.5%	0.0%	10.0%	10.0%	10.5%	0.0%	0.82
3	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	13.5%	0.0%	0.0%	0.34
4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	14.4%	3.5%	0.0%	0.18
5	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	10.7%	0.0%	0.0%	0.31
6	5.0%	9.3%	1.0%	5.0%	0.0%	50.0%	13.0%	7.0%	0.0%	0.90
7	0.0%	0.0%	0.0%	14.5%	1.6%	0.0%	18.5%	28.5%	0.0%	0.63

Figure 4-3. Program credits for Student Outcomes (AY 2019-2020).

YALE SCHOOL OF ENGINEERING AND APPLIED SCIENCE

CHEMICAL ENGINEERING ABET OUTCOME REVIEW



Outcomes	Unsatisfactory	Acceptable	Exemplary
1	9%	38%	53%
2	7%	36%	56%
3	1%	58%	40%
4	0%	35%	65%
5	1%	59%	40%
6	6%	37%	56%
7	5%	32%	63%

View Course Summary

Figure 4-4. Overall course-based Student Outcomes assessment summary of Chemical Engineering Program for AY 2019-2020.

(ii) Details of course-based Student Outcomes assessment:

Here, the quantitative details of our course assessment tool are described. The resultant weight $W_j^{(k)}$ for Student Outcome (SO) j in course k is given by the formula

$$W_j^{(k)} = \sum_i \mathrm{w}_{ij}^{(k)} \omega_i^{(k)} ,$$

where $\omega_i^{(k)}$ is the weight for an item i of coursework (problem set, exam, lab report or project) towards the overall course grade, and $w_{ij}^{(k)}$ is the course assessment matrix, i.e., the weight of SO j for an item i of student work. These weights are assigned by the course instructors and are required to satisfy the following normalizations:

$$\sum_i \omega_i^{(k)} = 1 , \qquad \sum_{j=1}^{7} \mathrm{w}_{ij}^{(k)} = 1 .$$

These normalizations ensure that the sum of the weights for all Student Outcomes in each course sum to unity:

$$\sum_{j=1}^{7} W_j^{(k)} = 1 .$$

Figure 4-1 shows an example of a course assessment matrix $w_{ij}^{(k)}$. The last column shows the resultant weights $W_j^{(k)}$ for each of the Student Outcomes $j = 1 - 7$.

The performance $P_{j\,m}^{(k)}$ of a student m on Student Outcome j in course k is given by

$$P_{jm}^{(k)} = \frac{1}{W_j^{(k)}} \sum_i \mathrm{w}_{ij}^{(k)} \omega_i^{(k)} s_m^{(k)} ,$$

where $0 \le s_{m\,i}^{(k)} \le 1$ is the fraction of the maximum score that student m received on coursework item i in course k. The fraction $f_{s,j}^{(k)}$ of students with satisfactory performance on SO j in course k is equal to the number of students with performance on SO j in the range: $P_s^{(k)} \le P_{jm}^{(k)} \le P_e^{(k)}$ divided by the number of students in the course, where $P_s^{(k)}$ and $P_e^{(k)}$ are the performance cut-offs for satisfactory and exemplary performance pre-assigned by the instructor of the course. The fractions $f_{e,j}^{(k)}$ and $f_{u,j}^{(k)}$ of students with exemplary and unsatisfactory, respectively, are calculated from the fractions of students with performances outside this range, i.e., $P_{jm}^{(k)} > P_e^{(k)}$ and $P_{jm}^{(k)} < P_u^{(k)}$. The summary performance for Chemical Engineering Process Design (CENG 416) is shown in Figure 4-2. Analyses for the other core courses will be available during the visit and are online at https://seas.yale.edu/seas-abet/2020/chemical-engineering-student-outcomes.

The results of our course-based Student Outcomes assessment are readily aggregated to provide an overall assessment for the Program. The overall Program weight for Student Outcome j is given by the sum over the K core courses that are included in the Self-Study,

$$W_j = \sum_{k=1}^{K} W_j^{(k)} \,,$$

where this formula assumes that the K courses have equal weight (credit), which is indeed the case for the courses included in our Self-Study. The Program weights are converted to credits by the product $K\,W_j$. The fraction of students achieving unsatisfactory, satisfactory, and exemplary attainment for each Student Outcome ($j = 1 - 7$) in our Program is obtained as an average of the fractions achieved in each of the courses included in this assessment.

(iii) Results of course-based Student Outcomes assessment:

The results of our course-based Student Outcomes assessment for Academic Year 2019–2020 are shown in Figures 4-3 and 4-4. The program weights are shown in Figure 4-3 and the levels of attainment for each Student Outcome are shown in Figure 4-4.

These results are important, as they serve to indicate the emphasis that our program places on each of the SOs and the degree to which the SOs were attained during Academic Year 2019–2020 based on the students' course performance. The results in Figure 4-4 indicate that over 90% of students in our Program are attaining at least a satisfactory level in all SOs. The uneven course credits devoted to each of the SOs seen in Figure 4-3 is noteworthy. However, this seems to be an artifact of limiting the spreadsheet analysis to include only the nine core courses, a quarter of the 36 courses required for graduation from Yale College.

Retaining the five credits of advanced chemistry (CHEM 220, 221, 222L, 223L, 332, 333) would have contributed significantly to SO 6. Several of the most common elective courses contribute to SOs 2, 4 and 7 (e.g. CENG 373, 377); Independent Study Research (CENG 471) contributes to SO 2, 3, 6, and 7. Table 5-2 in Chapter 5 shows the impact of retaining the advanced chemistry courses and a sample of elective courses (the ones whose syllabi appear in Appendix A) on the credit-weighting of SOs in the Chemical Engineering Program.

In our next spreadsheet analysis, we should retain the chemistry courses in the analysis. Incorporating the three engineering electives is more important but remains a challenge, given that students will make different choices. Even so, this approach neglects the nine credits of Yale College distributional requirements (Humanities, Social Sciences, Writing, and Languages), which may contribute towards SOs 2–5 and 7. To accurately assess the attainment of all Student Outcomes, all courses should be included at least in some approximate way.

2. Faculty reviews of capstone design course

The second method for measuring the attainment of Student Outcomes is based on a review of the team-based capstone projects in "Chemical Engineering Process Design" (CENG 416). Program Faculty review the senior class capstone design projects and are asked to rate the degree to which each of the SOs is achieved, on a 0 to 5 scale. Since the capstone design experience represents a culmination of all that is learned throughout the curriculum, such an assessment essentially covers the entire curriculum.

The averaged results of the 2020 capstone design project assessment appear in Table 4-1. These results indicate the SOs to be reasonably well attained for all teams, with Team 1 the best. The performance of our seniors in their capstone design project lends support to the assertion that our seniors graduate with a satisfactory level of all Student Outcomes, as seen in Table 4-1. These results are typical of previous years.

Table 4-1. 2020 Program Faculty Review of the Extent to which Student Outcomes are Attained through the Senior Capstone Design Projects.

scale: (0 = not attained, 5 = fully attained)

Student Outcome	1	2	3	4	5	6	7
Team 1	5.0	5.0	4.5	4.5	5.0	4.5	4.5
Team 2	4.7	4.8	4.5	4.1	5.0	4.3	4.3
Team 3	4.2	4.3	4.3	4.0	5.0	4.4	4.2

3. Biannual individual meetings with students

A third method for assessing achievement of the SOs is through biannual individual meetings between the DUS and the students in the Program. These one-on-one meetings help to assess whether individual students are making progress towards attainment of the Student Outcomes. These meetings serve as an early alert to take corrective action to address deficiencies in individual students and/or the courses in the Program. The broader information gathered from these individual meetings helps us to continuously improve the Program, as described below in Section B.

4. Surveys of students

A fourth method for assessing Student Outcomes is through anonymous surveys of our current students. The DUS administers anonymous online surveys to our current students annually or as needed, asking them questions aimed at assessing the efficacy of our program with regards to attaining Student Outcomes and/or the match between the career goals and our Program Educational Objectives. Online course evaluations at the end of each semester are required from all students, and these provide similar anonymous feedback that is readily available to the Program DUS. The standard questions on course evaluations provide an indirect assessment of the contribution of the course to SOs. The aggregated anonymous feedback from these surveys complements the information gained from individual meetings with students (item 3 above). Together the anonymous survey data and meetings with individual students provide valuable input for improving our program, as described in Section B.

5. Exit interviews of graduating seniors

The fifth method of Student Outcomes assessment is exit interviews by the DUS with graduating seniors. This involves a survey of the student's self-assessment of their achievement of the SOs and an informal discussion about positive and negative aspects of the program. The survey provides another indirect measure of our students' attainment of the Student Objectives, and the discussion can elicit suggestions for improvements while the students' experiences are fresh. Examples of data gathered from exit interviews are discussed below in Section B.

6. Surveys of recent graduates

The sixth method for assessing SOs (and Program Educational Objectives) is through anonymous surveys of recent graduates from our Program. These are annual anonymous online surveys administered by the DUS with questions aimed at evaluating the relevance of our Program Educational Objectives to their current career trajectory but also asking them to self-assess their attainment of the SOs at the time of their graduation. Typically, these surveys show a shift towards higher self-assessment of their achievement of SOs relative to students who are still in midst of the Program, especially with regard to the less tangible Student Outcomes, e.g., SOs 3 through 5. The use of survey data gathered from recent graduates is discussed in Section B.

Aggregation and evaluation of Student Outcomes assessment methods

A portion of faculty meetings are devoted to discussing the data generated by any of these six assessment methods, evaluating the extent to which the Student Outcomes are being attained, and implementing Program improvements. Examples of how the assessment methods are used is described below in Section B.

Documenting results of Student Outcomes assessment methods

Assessment Method 1 is the course-based performance evaluation process is based on course-specific grading spreadsheets. The DUS collects the spreadsheets and sends them to the School of Engineering & Applied Science (SEAS) Dean's Office, where they are saved in a central location and combined to produce the composite view of the Program's coverage. The Program also documents the results from the other assessment methods. The instructor of the senior capstone design course collects and aggregates the project reviews of the faculty (Assessment Method 2). Assessment Methods 3 through 6 are administered by the Program DUS, who retains surveys and archives a summary of interviews.

B. Continuous Improvement

Our Program's process for continuous improvement using the above assessment tools is illustrated in this section with a few examples. These examples show how (I) problems are identified through the above Assessment Methods (AMs), and (II) actions are taken and the problems re-assessed and further action taken as needed. In addition, this section details the undergraduate teaching lab improvements in the Chemical Engineering program, with this aspect summarized in section III.

I. Problems identified

Since the last Self-Study in 2014, six problems were identified. Each of these problem is described below, including the Assessment Methods that helped identify them.

1. Problem: Adapting *to students' preparation*

   During the last Self-Study in 2014, we had just implemented the requirement that students in our Program had to complete Introduction to Computing for Engineers and Scientists (ENAS 130) to satisfy the computing requirement. This one-credit course was assigned ½ credit basic math and science and ½ credit engineering topics.

   In individual meetings with our students (AM 3), the DUS learned that ENAS 130 was a poor fit for many students in our Program, either because they had a strong background in computer programming from high school or because they were interested in pursuing further computer programming and ENAS 130 is a terminal course by design. For these students, the one-size-fits-all requirement of taking ENAS 130 to satisfy the computing portion of the Program was discouraging to prospective Chemical Engineering majors and made little sense.

   In 2014, the Department of Computer Science was not part of SEAS. Therefore, a computer programming course from the Department of Computer Science could not reasonably be assigned engineering credit. Therefore, our students did not have the option of taking a more advanced computing course.

2. Problem: Difficulty finding internships and jobs in industry.

   Around 2015, it became evident that our students were having a harder time pursuing careers in industry. Part of this problem arose from the waning proportion of students heading to engineering graduate school, as revealed in exit interviews with our students (AM 5) in 2015 and 2016. In years past, many of our students pursued PhD's in engineering after graduation. For that path, experience in laboratory research was more important than a summer internship.

   As the career objectives of our students shifted, it became more important that our students have summer internships. DUS meetings with students in the Program (AM 3) and exit interviews with graduating seniors (AM 5) in 2015 and 2016 revealed that finding jobs in industry was becoming more difficult. Summer internships had become more important, if not essential, to ensure that our students could pursue their chosen career path after graduation.

   For a number of reasons (e.g., small program size), Yale has not attracted recruiting fairs from industrial firms looking for engineers to hire for summer internships or permanent jobs. Moreover, Yale's Office of Career Strategy does not have the same level of focus on engineering internships and jobs as a career services office would have at a more traditional engineering school. Our students therefore have had an added challenge finding internships and jobs in industry.

3. Problem: Uneven workload

A series of in-person meetings (AM 3) between the DUS and the Class of 2017 (during 2016, when they were in their junior year) revealed a strong and unified dissatisfaction with the curriculum. The Department Chair at the time, Professor Kim, also met with these students. These meetings revealed that the crux of the students' dissatisfaction lay in the highly uneven course load through the four-year program: a relatively light course load in sophomore year and a punishing load in junior year. The particularly time-consuming course was a full one-credit physical chemistry lab (CHEM 330L) that seemed to make the fall term of their junior year notoriously onerous. Exit interviews of seniors (AM 5) and surveys of recent alumni (AM 6) supported this view. Indeed, students sometimes dropped out of the accredited program to avoid the course load of the ABET Program during the fall semester of their junior year. In this way, Problems 3 and 4 are intertwined, as will be seen shortly.

4. Problem: Prospective students dropping from the major

By Spring 2017, it had become apparent that the enrollment in our sophomore-level introductory course Principles of Chemical Engineering and Process Modeling (CENG 210) was approximately twice as large as the number of students who were in the chemical engineering major one year later. In other words, half of the students were dropping out of the major between sophomore and junior years. Student surveys administered by the DUS and course evaluations (AM 4) indicated that CENG 210 was not attracting students to the major; only students who were determined to study chemical engineering stayed in the program (paraphrasing a frequent comment). Graduating seniors (AM 5) and recent alumni (AM 6) concurred, reporting that they were much more engaged by the junior year courses that followed a whole year after CENG 210.

In sum, the late introduction to the major (first semester sophomore year), the lackluster course experience, and the one-year delay for another chemical engineering course seemed a likely cause for having prospective majors lose interest.

5. Problem: Lack of diversity within the major

From individual meetings around the same time with students currently enrolled in CENG 210 and those who had recently taken the course (AM 3), the DUS noted that women and students of color seemed to be disproportionately dropping the major (especially women of color), leaving behind a Chemical Engineering class with less diversity than Yale College as a whole. While the numbers of students were too small to draw a definitive conclusion, the result was worrying. This problem was clearly correlated to the broader problem of losing prospective Chemical Engineering majors (Problem 4), but it highlights a troubling aspect.

6. Problem: Coordination of courses

   For many years, the department relied on a mechanical engineering fluid mechanics course (Mechanical Engineering II: Fluid Mechanics, MENG 361). Our students took MENG 361 in the first semester of their junior year and a Chemical Engineering transport course (Transport Phenomena, CENG 315) in the second semester of their junior year. Naturally, MENG 361 and CENG 315 were not ideally coordinated because MENG 361 was designed for the mechanical engineering major. Instructors of CENG 315 had grown accustomed to compensating for the mismatch by teaching some fluid mechanics in transport phenomena, covering topics that are not typically covered in a mechanical engineering fluids course, e.g., flows having a low Reynolds number.

   Exit interviews (AM 5) occasionally revealed that the students saw the inefficiency of this arrangement and brought this problem to our attention. However, it remained in our Program until student surveys (AM 4) in 2019 revealed a particularly strong dissatisfaction with the course because of its mismatch to their preparation and needs.

II. Actions taken and results

1. Action taken: Allow options for computing requirement

   Problem 1 was simple to solve, thanks to events external to the Department. In 2015, the Department of Computer Science expanded greatly and joined SEAS. (The timing of this expansion coincided with the resurgence of interest in data science.) Across the ABET-accredited programs in SEAS, it was felt that this restructuring lent credence to assigning partial engineering credit for a broader range of more advanced computing courses.

   Result:

   Feedback obtained from individual meetings between the DUS and students (AM 3) indicated that students were pleased to have options for satisfying their computing requirement, although it is rarely the case that students actually elect to take a more advance computing course to satisfy the requirement.

2. Actions taken: Development of intradepartmental resources for internships and jobs.

   Problem 2 has been harder to solve. Two attempts have been made to help our students find summer internships and jobs in industry since 2016.

   (i) Our first attempt to help students find internships and jobs in industry was the development of a Yale Chemical Engineering Alumni webpage in 2016 with contact information of recent undergraduate alumni, as well as alumni of our graduate program. It was intended be a growing resource of employers for potential internships and jobs for our students, as well as a resource for our alumni seeking engineers to hire. Even with only a few dozen alumni contacts, our webpage provided useful contact information that led to summer internships for some of our students, according to meetings with students and exit interviews (AM 3, AM 5). The plan was to collect contact information from students before they graduated and add their contact information to our webpage. By collaborating with the Office of Career Strategy (OCS), it was hoped that this webpage would be maintained and updated as alumni contact information changed. However, OCS could not take on this task. Unfortunately, without regular updating of contact information, the utility of the webpage faded (AM 3).

(ii) Our next attempt to help students find engineering internships and jobs was the formation of a Yale Chemical Engineering LinkedIn Group in 2018. Students join the group while enrolled in our Program. Updating contact information is unnecessary because LinkedIn accounts are retained when alumni change jobs.

Result:

The LinkedIn group now has approximately 10 years' worth of alumni from our Program (nearly 200 members). It is a more robust resource for our students and alumni and a considerable improvement over what students had access to in 2016, according to discussions with our students (AM 3, AM 5). It also provides a tool for surveying our alumni (AM 6), who seem energized to help find internships and jobs for students in our Program. The LinkedIn group is not yet a perfect solution, because group members rarely check their LinkedIn messages, but it is a definite improvement over the alumni webpage that we had implemented initially. The current effort (just underway) is to have members provide more active contact information, e.g., an email address.

3. Action taken: Redistribute workload by revising the chemistry lab requirement

The solution to Problem 3 was suggested by students in our meetings (AM 3): replace the one-credit Physical Chemistry Lab (CHEM 330L) by 2 half-credit Organic Chemistry Labs (CHEM 222L, 223L). An anonymous survey regarding this proposed solution was administered to ensure that all voices were heard (AM 4). The survey results showed that the proposal was strongly supported by students in the Class of 2017 with no opposition. The proposed solution was good for several reasons, as discussed below.

First, Organic Chemistry lectures are taken in our students' sophomore year. The proposed revision would help to redistribute their workload more evenly, thus relieving the junior year — especially the fall term of junior year. (Further action to redistribute the workload was achieved by moving the introductory course from sophomore to freshman year (see item 4 below).)

Second, the suggestion was pedagogically sound. The Organic Chemistry lecture sequence (CHEM 220, 221) is closely coordinated with the laboratory sequence (CHEM 222L, 223L). Taking the Organic Chemistry labs along with the Organic Chemistry lectures would allow our students to learn the material according to the design of the Chemistry Department. The same close coordination is not true of the Physical Chemistry sequence (CHEM 332, 333) and the Physical Chemistry Lab (CHEM 330L).

Third, from our discussions (AM 3), it seemed that the Organic Chemistry lab sequence was also better aligned with our students' interests and professional goals. Some students posited that the Organic Chemistry labs were better preparation for work in industry. Chemistry-oriented students had often wanted to take the Organic Chemistry labs and sometimes did so voluntarily, without receiving credit towards their major requirements.

With these points in mind, the DUS reached out to colleagues at ABET Chemical Engineering Programs at several other institutions to learn what was being done elsewhere. It was clear that the suggested replacement of the Physical Chemistry lab by the Organic Chemistry lab sequence would not be out of line with ABET programs elsewhere. In fact, our advanced chemistry requirement exceeds that of most other ABET programs.

We had been assigning the Physical Chemistry lab ½ credit science and ½ credit engineering because of the nature of the material. The content of the Organic Chemistry lab sequence appeared to meet the same criterion: the experiments included several topics of chemical engineering relevance, including distillation, crystallization, and extraction. With this in mind, the DUS presented the case for the proposed substitution in a faculty meeting, where it was adopted.

Result:

Individual meetings with the DUS (AM 3) and subsequent exit interviews with graduating seniors (AM 5) concurred that the students in the Program were pleased with the revision, especially because of the workload redistribution it created. The loss of students from the accredited major in the junior year has correspondingly diminished, thus helping with Problem 4 (see item 4 below).

4. Actions taken: New introductory course offered in the freshman year

Our primary approach to Problem 4 was the development of a new introductory course taught by the Program DUS. Actions taken for Problem 3 also helped as explained above.

In Spring 2018, course evaluations (AM 4) for CENG 210 (Principles of Chemical Engineering and Process Modeling) had not measurably improved, despite attempts on the part of the instruction to execute the course better. The Program DUS proposed that our introductory course be completely rebuilt with the aim of attracting students to the Chemical Engineering major. In particular, the new introductory course would be made accessible to students with a minimal background in chemistry and mathematics (single-variable calculus and general chemistry), so that it could be taken by students in their first year of college. The proposed course, Engineering Improv: An Introduction to Engineering Analysis (CENG 150), was designed to be accessible also to non-majors. The DUS assembled a detailed course proposal and presented it to the Program Faculty.

A healthy debate ensued among the Program Faculty about making the course more accessible. Would it fail to teach the basic principles that Chemical Engineering majors need in subsequent courses? Would it retain unqualified students in the major? By making the course engaging to students outside of the major, the DUS felt that it would make the major more appealing to prospective Chemical Engineering majors. The DUS also thought that making the course accessible to students in their first year (instead of making them wait to take their first CENG course until sophomore year) might increase retention of more prospective Chemical Engineering majors. A last point in favor of the new course was that it would further help to even out the workload distribution (Problem 3).

The Program Faculty eventually agreed to the idea of the new course. The DUS submitted a course proposal for CENG 150 to the Yale College Course of Studies Committee, and the proposal was approved.

Result:

The new course — Engineering Improv: An Introduction to Engineering Analysis (CENG 150) — was first offered in Spring 2019 and has become an integral part of the Chemical Engineering curriculum. The course rigorously covers mass and energy balances and mathematical process modeling. Unlike its predecessor CENG 210, CENG 150 also provides an introduction and overview of the whole chemical engineering curriculum, including units on thermodynamics, transport, kinetics, and separations. In each subsequent semester, the DUS has administered surveys of the 29 Chemical Engineering students who took the course in Spring 2019. The purpose of these surveys has been to assess the course's efficacy in helping students achieve the Student Outcomes (AM 4). The results indicated that the course is effectively preparing students, and the Program Faculty concurred. Similar findings were obtained when the course was taught again in Spring 2020.

The course has also attracted non-majors, demonstrating that the material is generally accessible to students with a minimal STEM background and is engaging to a broader range of students. This claim is supported by the end-of-semester course evaluations (AM 4).

The new course appears to be sharply improving retention in the Chemical Engineering major — only one student dropped the CENG 150 in Spring 2019 and all but one of the 29 prospective chemical engineering majors who completed the course have remained in the Program. No students dropped the course in Spring 2020. Students continue to occasionally switch out of the ABET-accredited major to the less-intensive major, Engineering Science (Chemical), but they remain in the field, either becoming employed as chemical engineers after graduation or going on to graduate study in chemical engineering.

5. Action taken: New first-year introductory class taught by the DUS

   Having the DUS teach the new introductory course CENG 150 starting in Spring 2019 was intended to help address the loss of prospective students from the Program (Problem 4), particularly the loss of women and students of color (Problem 5), by providing students easier and earlier access to the Program DUS and thereby more support.

   In our small program, the Program DUS is the point person for Chemical Engineering majors, serving as their academic advisor and liaison between them and instructors in other courses and their residential college deans as needed. Having the DUS teach the entry-level course helps to establish this relationship from the outset, providing students with more access to their advisor and enabling the DUS to more reliably supervise the progress of student towards the Student Outcomes.

   Result:

   By closely interacting with prospective students in their first year, the DUS can more actively intervene when needed. For example, the DUS can encourage well-qualified prospective students (women and students of color) who might otherwise feel out of place or intimidated by the prospect of pursuing a degree in Chemical Engineering, a traditionally white male field. While it is difficult to objectively assess the efficacy of this intervention, anecdotal evidence and the Program DUS's experience (AM 3) suggests that it may be helping.

   In a parallel effort to engage first-year students in engineering, SEAS organizes events for prospective engineering students to meet engineering DUSs and upperclassmen engineering majors and learn about the engineering programs at Yale. Anecdotal evidence suggests that these efforts are also helping to retain women and students of color in the Chemical Engineering major.

6. Action taken: Two-term chemical engineering transport sequence introduced

   With extra teaching resources available due to recent hires in the department, the DUS suggested in Spring 2020 that a two-semester transport sequence replace the historically mismatched courses described in Problem 6: Mechanical Engineering II: Fluid Mechanics (MENG 361) and Transport Phenomena (CENG 315). The Program Faculty supported the DUS's proposal, and the DUS submitted a new course proposal for Transport Phenomena I (CENG 314) to the Yale College Course of Studies Committee in June 2020, which was approved. The new course covers fluid mechanics in the framework of transport phenomena and is properly coordinated with CENG 315. The latter course is being correspondingly retitled Transport Phenomena II.

   Result:

   Starting with Fall 2020, juniors in the program will take the new two-semester transport sequence, Transport Phenomena I and II (CENG 314, 315). Individual meetings between students and the DUS (AM 3) and anonymous surveys (AM 4) will provide an initial assessment on how well the new course sequence helps achieve Student Outcomes.

III. Lab infrastructure improvement

The investments made to infrastructure within the Chemical Engineering program since 2014 have been significant. As detailed in Chapter 7 of this Self Study, as well as in press reports during this period (see https://yaledailynews.com/blog/2017/11/16/new-lab-space-centralizes-seas/), the creation of the Linda and Glenn H. Greenberg Engineering Teaching Concourse (GETC) has contributed to the program's success. This facility was opened in 2017 to provide new lab space and equipment for all of Yale's engineering programs, thereby replacing the previous electrical engineering teaching labs that were constructed over 50 years ago with facilities available and suitable for all engineering programs. Of note with respect to the Chemical Engineering program and the new labs (which total 10,000 square feet) are two wet labs which are ideal for program instruction.

As described in greater detail in Chapter 7 of this Self Study, he GETC facility includes six independent dry labs and two wet-labs, as well as storage space for program equipment that is not currently being used. As multidisciplinary spaces that were designed to offer full visibility into each lab from a common hallway, the new labs have the added benefit of being a showcase for the program's lab courses. By design, prospective students, visitors, and other members of the Yale community have an unimpeded ability to witness the actions and activities of the program's students and faculty as they work in a state-of-the-art facility to learn basic and advance fundamentals and to design new electrical and electronic products. The new facilities are highly valued by the program's students as they provide spacious room, modern design, and advanced equipment to engage in product courses and design projects. This infrastructure investment has also been accompanied by an investment in related Chemical Engineering lab experiments as detailed in Chapter 7 of this Self Study. Of note is that the 2014 ABET Review helped initiate this project as it was noted during the review that the undergraduate teaching labs at that time were not at an acceptable level of quality.

CRITERION 5. CURRICULUM

A. Program Curriculum

Table 5-1 appears on the next two pages and describes the curricular path to attain the B.S. degree in Chemical Engineering for the Class of 2020. Note that the requirements for the B.S. degree in Chemical Engineering for the Class of 2022 and beyond have changed and will be described in detail in Chapter 4. For the Class of 2022 and beyond, students will be required to take CENG 314 (Transport Phenomena I— a new course in Fall 2020) instead of MENG 361 (Mechanical Engineering II: Fluid Mechanics). All other requirements remain the same.

As can be seen from the table, Yale is on a semester system. There are 13.5 course credits (48 semester credit hours) in Math and Basic Sciences (i.e., mathematics, physics, and chemistry) and 13.5 course credits (48 semester credit hours) in Engineering Topics courses. The total of 27.0 course credits for the B.S. degree in Chemical Engineering is broken down into 19.0 course credits for required courses and 8.0 course credits for prerequisites. Three of the Engineering Topics courses are electives that can be chosen from a pool of more than 20 courses that are taught at least every other year.

In addition to the 27.0 course credits required for the B.S. degree in Chemical Engineering, there are 9.0 course credits (27.0 semester credit hours) necessary to satisfy the distributional requirements for Yale College; these credits are spread across humanities, social sciences, writing, and languages. Thus, to obtain the B.S. degree in Chemical Engineering, students need 36.0 course credits, thus meeting the Yale College minimum for graduation, which is 36.0 course credits.

It should be noted that the table shows the Chemical Engineering curriculum for a student who, upon entering Yale, has minimal preparation in mathematics and chemistry. However, a student who passes an advanced prerequisite in mathematics is automatically considered to have demonstrated proficiency in the lower-level mathematics prerequisite courses without actually taking them. Similarly, a student who takes CHEM 174 (Organic Chemistry for First-Year Students I) and CHEM 175 (Organic Chemistry for First-Year Students II) during his/her first-year, along with the Organic Chemistry laboratories (CHEM 222L, 223L), is automatically considered to have demonstrated proficiency in the lower-level chemistry prerequisites (CHEM 134L, 136L, 161, and 165). Such a student would end up taking additional courses in humanities, social sciences, writing, and/or languages in order to meet the minimum number of course credits (36.0) required of every undergraduate at Yale.

Table 5-1 is discussed in greater detail later in this chapter, in the subsection entitled "How the Curriculum Meets Requirements for Math & Basic Sciences and Engineering Topics."

Table 5-1. Curriculum.
Chemical Engineering: Bachelor of Science

Course (Department, Number, Title) List all courses in the program by term starting with the first term of the first year and ending with the last term of the final year.	Indicate whether course is Required, Elective or a Selected Elective by an R, an E or an SE.[1]	Subject Area (Credit Hours)			Last Two Terms the Course was Offered: Year and, Semester, or Quarter	Maximum Section Enrollment for the Last Two Terms the Course was Offered[2]
		Math & Basic Sciences	Engineering Topics; Check if Contains Significant Design (✓)	Other		
First-Year Fall:						
MATH 112: Calculus of Functions of One Variable I		3.0			F19, SP20	139
CHEM 161: General Chemistry I		4.0			F19, SP20	258
CHEM 134L: General Chemistry Laboratory I		1.5			F19, SP20	282
Two Humanities/Social Science/Writing/Language Electives				6.0	F19, SP20	
First-Year Spring:						
MATH 115: Calculus of Functions of One Variable II		3.0			F19, SP20	267
CHEM 165: General Chemistry II		4.0			F19, SP20	196
CHEM 136L: General Chemistry Laboratory II		1.5			F19, SP20	226
CENG 150: Engineering Improv: An Introduction to Engineering Analysis	R		3.0		SP19, SP20	35
One Humanities/Social Science/Writing/Language Elective				3.0	F19, SP20	
Sophomore Fall:						
ENAS 151: Multivariable Calculus for Engineers		3.0			F19, SP20	84
CHEM 220: Organic Chemistry	R	4.0			F19, SP20	224
CHEM 222L: Laboratory for Organic Chemistry I	R	0.75	0.75		F19, SP19	310
PHYS 180: University Physics I		4.0			F18, F19	277
One Humanities/Social Science/Writing/Language Elective				3.0	F19, SP20	
Sophomore Spring:						
ENAS 194: Ordinary and Partial Differential Equations with Applications	R	3.0			F19, SP20	76
CHEM 221: The Organic Chemistry of Life Processes	R	4.0			SP19, SP20	169
CHEM 223L: Laboratory for Organic Chemistry II	R	0.75	0.75		SP19, SP20	220
PHYS 181: University Physics II		4.0			SP19, SP20	230

ENAS 130: Introduction to Computing for Engineers and Scientists	R	1.5	1.5		F19, SP20	66
Junior Fall:						
CHEM 332: Physical Chemistry with Applics. in the Physical Sciences I	R	2.0	2.0		F18, F19	66
CENG 300: Chemical Engineering Thermodynamics	R		3.0		F18, F19	21
MENG 361: Mechanical Engineering II: Fluid Mechanics	R		4.0		F18, F19	52
Two Humanities/Social Science/Writing/Language Electives				6.0	F19, SP20	
Junior Spring:						
CHEM 333: Physical Chemistry with Applics. in the Physical Sciences II	R	4.0			SP19, SP20	40
CENG 301: Chemical Kinetics and Chemical Reactors	R		4.0		SP19, SP20	28
CENG 315: Transport Phenomena	R		4.0		SP19, SP20	32
One Humanities/Social Science/Writing/Language Elective				3.0	F19, SP20	
Senior Fall:						
CENG 411: Separation and Purification Processes	R		4.0		F18, F19	17
CENG 480: Chemical Engineering Process Control	R		4.0✓		F18, F19	10
Two CENG Electives	E		6.0		F19, SP20	
One Humanities/Social Science/Writing/Language Elective				3.0	F19, SP20	
Senior Spring:						
CENG 412L: Chemical Engineering Laboratory and Design	R		4.0✓		SP19, SP20	12
CENG 416: Chemical Engineering Process Design	R		4.0✓		SP19, SP20	13
One CENG Elective	E		3.0		F19, SP20	
One Humanities/Social Science/Writing/Language Elective				3.0	F19, SP20	
TOTALS (in terms of semester credit hours)		48 Hours	48 Hours	27 Hours		
Totals must satisfy minimum credit hours.	Minimum Semester Credit Hours	30 Hours	45 Hours			

1. **Required** courses are required of all students in the program, **Elective** courses (often referred to as open or free electives) are optional for students, and **Selected Elective** courses are those for which students must take one or more courses from a specified group.
2. For courses that include multiple elements (lecture, laboratory, recitation, etc.), indicate the maximum enrollment in each element. For Selected Elective courses, indicate the maximum enrollment for each option.

Instructional materials and student work verifying compliance with ABET criteria for the categories indicated above will be required during the campus visit.

Alignment of the curriculum with the Program Educational Objectives:

In this section, we describe the alignment of the courses in the curriculum (Table 5-1) to our five Program Educational Objectives (PEOs in Chapter 2.B). We note that some changes have recently been made in the requirements for the B.S. degree in Chemical Engineering to increase the alignment of the curriculum with the PEOs. Chapter 4 describes how the previous Physical Chemistry laboratory requirement was replaced with an Organic Chemistry lab sequence requirement, aligning better with student career interests (thus promoting several of the PEOs) and with ABET-accredited programs at peer institutions. Chapter 4 also describes the fact that the previous gateway course into the Chemical Engineering major (CENG 210: Chemical Engineering and Process Modeling) was replaced by a new course (CENG 150: Engineering Improv: An Introduction to Engineering Analysis), which has improved students' broad knowledge of Chemical Engineering early in their college educations and has increased the number of women and students of color in the major (thus also promoting several of the PEOs).

Overall, the curriculum leads to a strong foundation in Chemical Engineering, the underlying basic sciences, and in general education. It also allows for sufficient flexibility so as to develop individual student interests. The Program Faculty strongly believe that such a foundation prepares students well for their future paths, in particular, professional practice or graduate / professional school. Hence, the curriculum is in strong support of PEOs 1, 2, 3, and 4. It should also be noted that the foundational science / engineering knowledge, the general education knowledge, and (more broadly) the Yale Residential College experience all help students develop a sense of the human needs addressable through engineering, thus supporting PEO 2; these experiences also foster an enjoyment of learning, thus supporting PEO 5.

In the remainder of this section, we examine the alignment of the curriculum (using the major requirements that applied to the Class of 2020) with the PEOs. To determine which courses contribute to each of the PEOs, we begin by making use of the mapping between ABET Student Outcome (SO) and PEOs, which appeared in Chapter 3.B. It should also be noted that the SOs addressed by each course are provided in each course syllabus in Appendix A, along with specific outcomes of instruction. This information, coupled with the mapping, allows us to create the following lists of courses that contribute to satisfying each of the Program Educational Objectives. These lists show that many courses are aligned with each PEO.

PEO 1: Have mastery of the basic principles of science and modern chemical engineering practice and be able to adapt and creatively apply them to solve new problems in a broad range of fields.

Prerequisites:

- CHEM 134L: General Chemistry Laboratory I
- CHEM 136L: General Chemistry Laboratory II
- CHEM 161: General Chemistry I
- CHEM 165: General Chemistry II
- MATH 112: Calculus of Functions of One Variable I
- MATH 115: Calculus of Functions of One Variable II
- ENAS 151: Multivariable Calculus for Engineers

- PHYS 180: University Physics I
- PHYS 181: University Physics II

Required Courses:

- ENAS 130: Introduction to Computing for Engineers and Scientists
- ENAS 194: Ordinary and Partial Differential Equations with Applications
- CENG 150: Engineering Improv: An Introduction to Engineering Analysis
- CENG 300: Chemical Engineering Thermodynamics
- CENG 301: Chemical Kinetics and Chemical Reactors
- CENG 315: Transport Phenomena
- CENG 411: Separation and Purification Processes
- CENG 412L: Chemical Engineering Laboratory and Design
- CENG 416: Chemical Engineering Process Design
- CENG 480: Chemical Engineering Process Control
- CHEM 220: Organic Chemistry
- CHEM 221: The Organic Chemistry of Life Processes
- CHEM 222L: Laboratory for Organic Chemistry I
- CHEM 223L: Laboratory for Organic Chemistry II
- CHEM 332: Physical Chemistry with Applications in the Physical Sciences I
- CHEM 333: Physical Chemistry with Applications in the Physical Sciences II
- MENG 361: Mechanical Engineering II: Fluid Mechanics

Examples of Electives:

- CENG 351: Biotransport and Kinetics
- CENG 373: Air Pollution Control
- CENG 377: Water Quality Control
- CENG 471: Independent Research
- CENG 473: Air Quality and Energy
- MENG 280: Mechanical Engineering I: Strength and Deformation of Mechanical Elements
- MENG 285: Introduction to Materials Science
- MENG 365: Chemical Propulsion Systems
- MENG 383: Mechanical Engineering III: Dynamics
- MENG 441: Applied Numerical Methods for Differential Equations
- EENG 406: Photovoltaic Energy
- BENG 350: Physiological Systems
- BENG 353: Introduction to Biomechanics
- BENG 434: Biomaterials

PEO 2: Become ethical professionals who advance chemical engineering practice and knowledge in multiple fields and recognize the local and global impacts of their work on humans and the environment.

Prerequisites:

- CHEM 134L: General Chemistry Laboratory I
- CHEM 136L: General Chemistry Laboratory II
- CHEM 161: General Chemistry I
- CHEM 165: General Chemistry II
- MATH 112: Calculus of Functions of One Variable I
- MATH 115: Calculus of Functions of One Variable II
- ENAS 151: Multivariable Calculus for Engineers
- PHYS 180: University Physics I
- PHYS 181: University Physics II

Required Courses:

- ENAS 130: Introduction to Computing for Engineers and Scientists
- ENAS 194: Ordinary and Partial Differential Equations with Applications
- CENG 150: Engineering Improv: An Introduction to Engineering Analysis
- CENG 300: Chemical Engineering Thermodynamics
- CENG 301: Chemical Kinetics and Chemical Reactors
- CENG 315: Transport Phenomena
- CENG 411: Separation and Purification Processes
- CENG 412L: Chemical Engineering Laboratory and Design
- CENG 416: Chemical Engineering Process Design
- CENG 480: Chemical Engineering Process Control
- CHEM 220: Organic Chemistry
- CHEM 221: The Organic Chemistry of Life Processes
- CHEM 222L: Laboratory for Organic Chemistry I
- CHEM 223L: Laboratory for Organic Chemistry II
- CHEM 332: Physical Chemistry with Applications in the Physical Sciences I
- CHEM 333: Physical Chemistry with Applications in the Physical Sciences II
- MENG 361: Mechanical Engineering II: Fluid Mechanics
- Yale College Distributional Requirements (electives in Humanities, Social Science, Writing, and Languages)

Examples of Electives:

- CENG 351: Biotransport and Kinetics
- CENG 373: Air Pollution Control
- CENG 377: Water Quality Control
- CENG 471: Independent Research
- CENG 473: Air Quality and Energy
- MENG 280: Mechanical Engineering I: Strength and Deformation of Mechanical Elements
- MENG 285: Introduction to Materials Science

- MENG 365: Chemical Propulsion Systems
- MENG 383: Mechanical Engineering III: Dynamics
- MENG 441: Applied Numerical Methods for Differential Equations
- EENG 406: Photovoltaic Energy
- BENG 350: Physiological Systems
- BENG 353: Introduction to Biomechanics
- BENG 434: Biomaterials

PEO 3: Be able to work well with people from diverse backgrounds and be committed to the advancement of women and under-represented groups in engineering.

Required Courses:

- CENG 412L: Chemical Engineering Laboratory and Design
- CENG 416: Chemical Engineering Process Design
- CENG 480: Chemical Engineering Process Control

Examples of Electives:

- CENG 373: Air Pollution Control
- CENG 377: Water Quality Control
- CENG 471: Independent Research
- CENG 473: Air Quality and Energy
- MENG 383: Mechanical Engineering III: Dynamics
- EENG 406: Photovoltaic Energy
- BENG 434: Biomaterials

PEO 4: Have strong educational foundation enabling them to study in graduate and professional schools as well as become leaders in STEM or non-STEM career paths.

Prerequisites:

- CHEM 134L: General Chemistry Laboratory I
- CHEM 136L: General Chemistry Laboratory II
- CHEM 161: General Chemistry I
- CHEM 165: General Chemistry II
- MATH 112: Calculus of Functions of One Variable I
- MATH 115: Calculus of Functions of One Variable II
- ENAS 151: Multivariable Calculus for Engineers
- PHYS 180: University Physics I
- PHYS 181: University Physics II

Required Courses:

- ENAS 130: Introduction to Computing for Engineers and Scientists
- ENAS 194: Ordinary and Partial Differential Equations with Applications
- CENG 150: Engineering Improv: An Introduction to Engineering Analysis

- CENG 300: Chemical Engineering Thermodynamics
- CENG 301: Chemical Kinetics and Chemical Reactors
- CENG 315: Transport Phenomena
- CENG 411: Separation and Purification Processes
- CENG 412L: Chemical Engineering Laboratory and Design
- CENG 416: Chemical Engineering Process Design
- CENG 480: Chemical Engineering Process Control
- CHEM 220: Organic Chemistry
- CHEM 221: The Organic Chemistry of Life Processes
- CHEM 222L: Laboratory for Organic Chemistry I
- CHEM 223L: Laboratory for Organic Chemistry II
- CHEM 332: Physical Chemistry with Applications in the Physical Sciences I
- CHEM 333: Physical Chemistry with Applications in the Physical Sciences II
- MENG 361: Mechanical Engineering II: Fluid Mechanics
- Yale College Distributional Requirements (electives in Humanities, Social Science, Writing, and Languages)

Examples of Electives:

- CENG 351: Biotransport and Kinetics
- CENG 373: Air Pollution Control
- CENG 377: Water Quality Control
- CENG 471: Independent Research
- CENG 473: Air Quality and Energy
- MENG 280: Mechanical Engineering I: Strength and Deformation of Mechanical Elements
- MENG 285: Introduction to Materials Science
- MENG 365: Chemical Propulsion Systems
- MENG 383: Mechanical Engineering III: Dynamics
- MENG 441: Applied Numerical Methods for Differential Equations
- EENG 406: Photovoltaic Energy
- BENG 350: Physiological Systems
- BENG 353: Introduction to Biomechanics
- BENG 434: Biomaterials

PEO 5: Be committed to, and engage in, lifelong learning throughout their careers.

Prerequisites:

- CHEM 134L: General Chemistry Laboratory I
- CHEM 136L: General Chemistry Laboratory II
- CHEM 161: General Chemistry I
- CHEM 165: General Chemistry II

Required Courses:

- CENG 150: Engineering Improv: An Introduction to Engineering Analysis

- CENG 301: Chemical Kinetics and Chemical Reactors
- CENG 315: Transport Phenomena
- CENG 411: Separation and Purification Processes
- CENG 412L: Chemical Engineering Laboratory and Design
- CENG 416: Chemical Engineering Process Design
- CENG 480: Chemical Engineering Process Control
- CHEM 220: Organic Chemistry
- CHEM 221: The Organic Chemistry of Life Processes
- CHEM 222L: Laboratory for Organic Chemistry I
- CHEM 223L: Laboratory for Organic Chemistry II
- CHEM 332: Physical Chemistry with Applications in the Physical Sciences I
- CHEM 333: Physical Chemistry with Applications in the Physical Sciences II
- Yale College Distributional Requirements (electives in Humanities, Social Science, Writing, and Languages)

Examples of Electives:

- CENG 373: Air Pollution Control
- CENG 377: Water Quality Control
- CENG 471: Independent Research
- CENG 473: Air Quality and Energy
- MENG 365: Chemical Propulsion Systems
- MENG 383: Mechanical Engineering III: Dynamics
- MENG 441: Applied Numerical Methods for Differential Equations
- EENG 406: Photovoltaic Energy
- BENG 353: Introduction to Biomechanics
- BENG 434: Biomaterials

Curriculum's support of the attainment of Student Outcomes

Regarding the curriculum's support of the attainment of Student Outcomes, the course-based performance evaluation process described in Chapter 4 illustrates how the Chemical Engineering curriculum promotes SO attainment. In essence, this component of our assessment process is an explicit pairing between the relevant problems/assignments in each course and specific SOs.

For the curriculum taken by the Class of 2020, the coverage of Student Outcomes within each course is detailed in Table 5-2. (The SOs satisfied in each course are also indicated on the syllabi in Appendix A.) The table shows which courses help students to attain each of the SOs 1 through 7. We see that the mapping of SO 1 and SO 6 to a large number of courses ensures that students receive extensive breadth and depth in these two SOs. The remaining SOs are each covered by a smaller number of courses. The Yale College Distributional Requirements in Humanities, Social Science, Writing, and Languages further contribute to SOs 2–5 and 7 but are not included here. In any case, Table 5-2 shows that all seven SOs are covered by the Chemical Engineering curriculum.

Table 5-2. Relationship between curriculum and attainment of Student Outcomes.

Curriculum↓	Student Outcomes→	1	2	3	4	5	6	7
Prerequisites								
CHEM 134L	General Chemistry Laboratory I	x					x	
CHEM 136L	General Chemistry Laboratory II	x					x	
CHEM 161	General Chemistry I	x					x	
CHEM 165	General Chemistry II	x					x	
MATH 112	Calculus of Functions of One Variable I	x						
MATH 115	Calculus of Functions of One Variable II	x						
ENAS 151	Multivariable Calculus for Engineers	x						
PHYS 180	University Physics I	x						
PHYS 181	University Physics II	x						
Required Courses								
ENAS 130	Introduction to Computing for Engineers and Scientists	x						
ENAS 194	Ordinary and Partial Differential Equations with Applications	x						
CENG 150	Engineering Improv: An Introduction to Engineering Analysis	x	x				x	
CENG 300	Chemical Engineering Thermodynamics	x						
CENG 301	Chemical Kinetics and Chemical Reactors	x	x				x	
CENG 315	Transport Phenomena	x	x				x	x
CENG 411	Separation and Purification Processes	x						x
CENG 412L	Chemical Engineering Laboratory and Design		x	x		x	x	
CENG 416	Chemical Engineering Process Design	x	x	x	x	x	x	x
CENG 480	Chemical Engineering Process Control	x	x		x		x	x
CHEM 220	Organic Chemistry	x					x	
CHEM 221	The Organic Chemistry of Life Processes	x					x	
CHEM 222L	Laboratory for Organic Chemistry I	x					x	
CHEM 223L	Laboratory for Organic Chemistry II	x					x	
CHEM 332	Physical Chemistry with Applications in the Physical Sciences I	x					x	
CHEM 333	Physical Chemistry with Applications in the Physical Sciences II	x					x	
MENG 361	Mechanical Engineering II: Fluid Mechanics	x						
Examples of Electives (students take 3 electives)								
CENG 351	Biotransport and Kinetics	x	x					
CENG 373	Air Pollution Control	x	x	x	x	x	x	x

CENG 377	Water Quality Control	x	x		x			x
CENG 471	Independent Research	x		x			x	x
CENG 473	Air Quality and Energy	x	x	x	x	x	x	x
MENG 280	Mechanical Engineering I: Strength and Deformation of Mechanical Elements	x						
MENG 285	Introduction to Materials Science	x						
MENG 365	Chemical Propulsion Systems	x					x	x
MENG 383	Mechanical Engineering III: Dynamics	x		x				x
MENG 441	Applied Numerical Methods for Differential Equations	x					x	
EENG 406	Photovoltaic Energy	x	x	x	x		x	
BENG 350	Physiological Systems	x						
BENG 353	Introduction to Biomechanics	x					x	
BENG 434	Biomaterials	x	x		x		x	

Prerequisite structure of the Program's required courses:

This section describes the prerequisite structure of the Chemical Engineering Program. Additional details are provided in Chapter 1. It is noted that the terminology courses and credits are more or less interchangeable at Yale, with the majority of courses awarded one credit; the exceptions relevant for Chemical Engineering students are that the CHEM laboratory courses that they take (CHEM 134L, 136L, 222L, and 223L) are each awarded only one-half credit.

The Program requires prerequisite courses in mathematics, chemistry, and physics. In mathematics, the students must take, as prerequisites, courses up to and including Multivariable Calculus (ENAS 151 or MATH 120). In chemistry, students must take, as prerequisites, two terms of General Chemistry (CHEM 161 and CHEM 165) and both of the associated laboratory courses (CHEM 134L and CHEM 136L). In physics, students must take two terms of Calculus-based Physics (PHYS 180 and 181). The flowchart (Figure 5-1) below provides a guide for the mathematics, chemistry, and physics prerequisites for Chemical Engineering majors.

The specific set of prerequisites taken during the first year depends on the student's high school background and perceived capabilities. First-year students are advised by the Chemical Engineering DUS to seek the proper course level: a student should not repeat material taken in high school, nor should a student overreach and then perform poorly in a class. At Yale, students do not register for a course until 10 days after the term begins ("the Yale shopping period"). The shopping period allows students to sample the intensity and pace of multiple courses and to select courses appropriately. To assist the student in finding the appropriate introductory course, mathematics courses are taught in multiple sections with varying meeting times to avoid scheduling conflicts. In terms of fulfilling the mathematics prerequisites for the Chemical Engineering major, a student who passes an advanced prerequisite is automatically considered to have demonstrated proficiency in the lower-level prerequisite courses.

Required courses in the major must be taken after their own prerequisites; some of these prerequisites may be prerequisites for the major, while others may themselves be required courses in the major. Figure 5-1 displays a flowchart showing the order in which prerequisites and required courses must be taken.

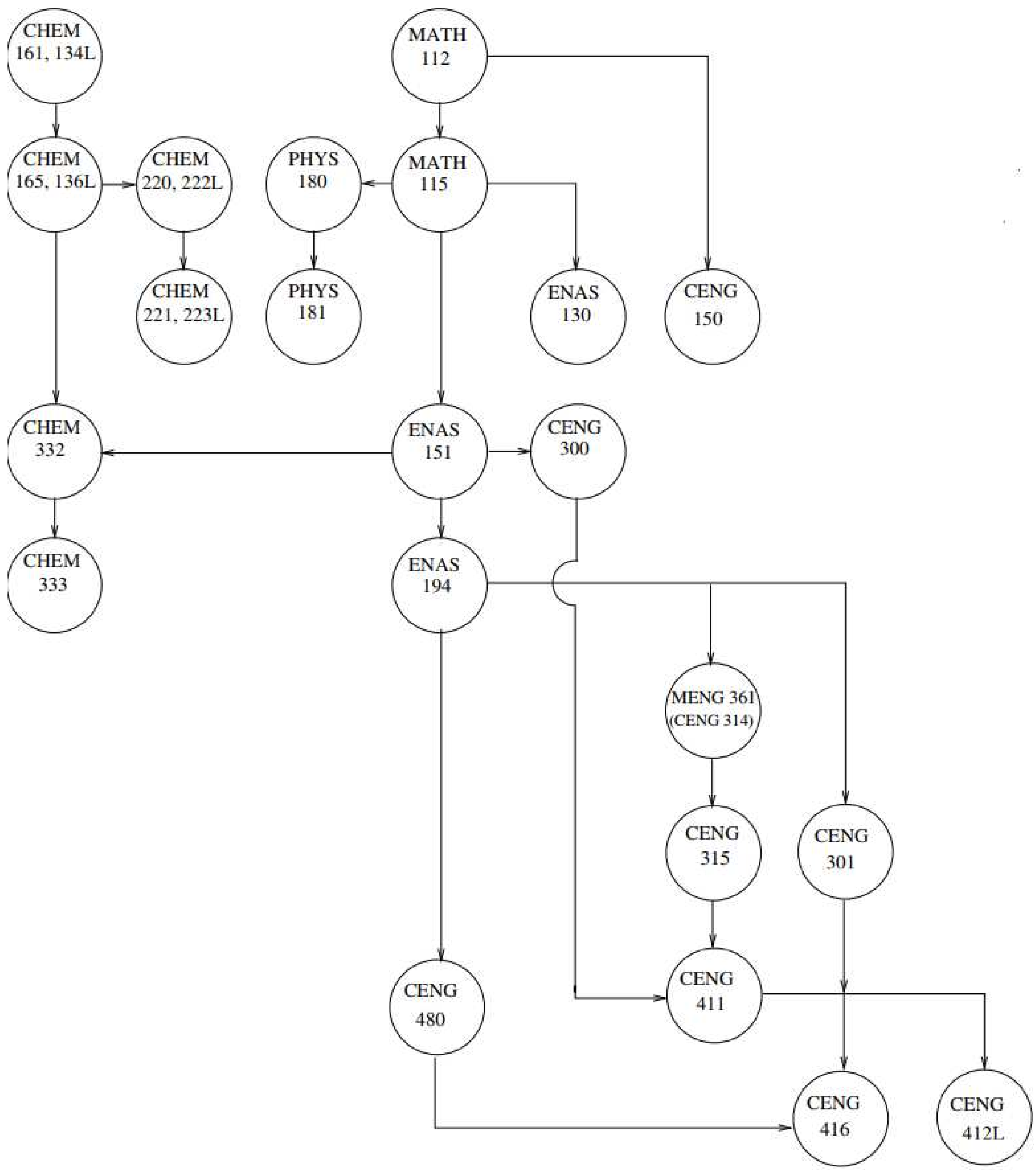


Figure 5-1. Flowchart of prerequisites for courses in the Chemical Engineering Program.

How the Curriculum Meets Requirements for Math & Basic Sciences and Engineering Topics:

A Yale Baccalaureate degree requires at least 36.0 credits, typically completed in 8 semesters (4 years). Yale University operates on a semester system. Each semester consists of 13 weeks of classes followed by a short reading period. Final examinations take place immediately following the end of reading period. The majority of Yale Engineering classes offer 2.5 hours of lectures per week (three 50-minute classes or two 75-minute classes) with an additional problem or recitation section. Laboratory and design-oriented classes typically offer one to two hours of lecture per week with additional hours spent in the lab. Since the laboratory and design classes are run in an open format, students typically spend considerably more time than the formally scheduled times.

Table 5-1 shows the Chemical Engineering curriculum for the minimum preparation in mathematics and chemistry, which totals 36.0 Yale course credits (123.0 credit hours). The courses are divided into three categories: Math and Basic Sciences; Engineering Topics; and Other. These categories contain 13.5 course credits (48 credit hours), 13.5 course credits (48 credit hours), and 9.0 course credits (27 credit hours), respectively.

The 13.5 Math and Basic Sciences course credits are as follows:

- General Chemistry Laboratory I (CHEM 134L, ½ course credit)
- General Chemistry Laboratory II (CHEM 136L, ½ course credit)
- General Chemistry I (CHEM 161)
- General Chemistry II (CHEM 165)
- Organic Chemistry (CHEM 220
- The Organic Chemistry of Life Processes (CHEM 221)
- Laboratory for Organic Chemistry I (CHEM 222L, ½ total course credit – counts ¼ credit in this category and ¼ course credit in Engineering Topics, below)
- Laboratory for Organic Chemistry II (CHEM 223L, ½ total course credit – counts ¼ credit in this category and ¼ course credit in Engineering Topics, below)
- Physical Chemistry with Applications in the Physical Sciences I (CHEM 332, 1 total course credit – counts ½ course credit in this category and ½ course credit in Engineering Topics, below)
- Physical Chemistry with Applications in the Physical Sciences II (CHEM 333)
- Calculus of Functions of One Variable I (MATH 112)
- Calculus of Functions of One Variable II (MATH 115)
- Multivariable Calculus for Engineers (ENAS 151)
- University Physics I (PHYS 180)
- University Physics II (PHYS 181)
- Introduction to Computing for Engineers and Scientists (ENAS 130, 1 total course credit – counts ½ course credit in this category and ½ course credit in Engineering Topics, below)
- Ordinary and Partial Differential Equations with Applications (ENAS 194).

The 13.5 Engineering Topics course credits are as follows:

- Introduction to Computing for Engineers and Scientists (ENAS 130, 1 total course credit – counts ½ course credit in this category and ½ course credit in Math and Basic Sciences, above)
- Laboratory for Organic Chemistry I (CHEM 222L, ½ total course credit – counts ¼ credit in this category and ¼ course credit in Math and Basic Sciences, above)
- Laboratory for Organic Chemistry II (CHEM 223L, ½ total course credit – counts ¼ credit in this category and ¼ course credit in Math and Basic Sciences, above)
- Physical Chemistry with Applications in the Physical Sciences I (CHEM 332, 1 total course credit – counts ½ course credit in this category and ½ course credit in Math and Basic Sciences, above)
- Engineering Improv: An Introduction to Engineering Analysis (CENG 150)
- Chemical Engineering Thermodynamics (CENG 300)
- Chemical Kinetics and Chemical Reactors (CENG 301)
- Transport Phenomena (CENG 315)
- Separation and Purification Processes (CENG 411)
- Chemical Engineering Laboratory and Design (CENG 412L)
- Chemical Engineering Process Design (CENG 416)
- Chemical Engineering Process Control (CENG 480)
- Mechanical Engineering II: Fluid Mechanics (MENG 361)
- and three electives.

The remaining 9.0 course credits are in the Other category. These courses are electives in humanities, social sciences, writing, and languages.

Regarding the Program's ability to meet the requirements in terms of hours and depth of study in Math and Basic Sciences, Engineering Topics, and General Education, Table 5.1 illustrates how the required criteria are met. The science portion of the curriculum consists of mathematics through differential equations, organic chemistry, physical chemistry, and calculus-based physics. As mentioned earlier in this chapter, many students come to Yale having completed sufficient math and/or chemistry so as to enter the curriculum at a higher point. These substitutions are all reviewed by the DUS during the freshman year, and any decisions are noted on the Course of Study Form.

For the Class of 2020, the engineering portion of the curriculum consists of eight CENG courses, one MENG course, and three engineering elective courses. These offerings sum to 12 engineering courses. (Beginning with the Class of 2022, the MENG course will be replaced with CENG 314: Transport Phenomena I, as described in Chapter 4.B.) In addition, the equivalent of 1.5 engineering course credits results from Introduction to Computing for Engineers and Scientists (ENAS 130 – taught by engineering faculty to a primarily engineering audience), Physical Chemistry with Applications in the Physical Sciences I (CHEM 332), and the two Organic Chemistry Labs (222L, 223L). These courses contain significant engineering content and have been counted as half engineering courses / half math and science courses in the Program since 2012. Additional justification appears below.

Introduction to Computing for Engineers and Scientists (ENAS 130) is an engineering course and is taught by engineering faculty. A review of the course material by the DUS has indicated that essentially all of the problems and examples from the lectures, problem sets, and exams are engineering-oriented. While some attention is rightfully given to the programming techniques themselves, the Program contends that ½ of an engineering credit is well merited. The course syllabus appears in Appendix A.

Laboratory for Organic Chemistry I (CHEM 222L) and Laboratory for Organic Chemistry II (CHEM 223L) are two ½-credit labs that include many experiments of chemical engineering relevance, including distillation, crystallization, and extraction. Direct hands-on exposure to these important topics provides valuable context for upper-level engineering courses such as Purification and Separation Processes (CENG 411), as well as additional training in safe laboratory practices. Accordingly, the Program contends that ½ of an engineering course credit for the combination of these two Organic Chemistry laboratory courses is a reasonable apportionment. The course syllabi for these labs appear in Appendix A.

Physical Chemistry with Applications in the Physical Sciences I (CHEM 332) covers three main topics: thermodynamics, electrochemistry, and kinetics. Thermodynamics and kinetics are important engineering topics that are also covered in pure engineering courses. Their inclusion in Physical Chemistry allows for more advanced coverage in the corresponding engineering courses. Since two of the three main topics (thermodynamics and kinetics) are central engineering topics, the Program contends that ½ of an engineering course credit for Physical Chemistry with Applications in the Physical Sciences I is a reasonable apportionment. The course syllabus appears in Appendix A.

Broad education component:

As stated on the Yale Admissions Office website, "Yale is committed to the idea of a liberal arts education through which students think and learn across disciplines, liberating or freeing the mind to its fullest potential. The essence of such an education is not what you study, but the result: gaining the ability to think critically and independently and to write, reason, and communicate clearly – the foundation for all professions… There are no specific classes you must take at Yale, but you are required to learn broadly and deeply." Students broaden their education by choosing from among hundreds of humanities, social science, and natural science courses, while they also learn one subject area (their chosen major) in depth.

To ensure that students have a broad educational experience, Yale College imposes specific graduation requirements relating to disciplinary areas and to skills. Regarding disciplinary areas, students are required to take no fewer than two course credits in the humanities and arts (Hu), two course credits in the sciences (Sc), and two course credits in the social sciences (So). The two course credits in the sciences are fulfilled by the Chemical Engineering Program requirements in Chemistry and Physics. Students must also fulfill skills requirements by taking two course credits in quantitative reasoning (QR), two course credits in writing (WR), and courses to further their foreign language proficiency. The two required course credits in quantitative reasoning are fulfilled by the prerequisite and/or required mathematics courses for the Chemical Engineering Program. Depending on their level of accomplishment in foreign languages at matriculation, students may fulfill this last requirement with one, two, or three courses or by a combination of coursework and approved study abroad.

Courses that fulfill the distributional requirements are designated in the course listings in Chapter IV of the Yale College Programs of Study (YCPS) by the abbreviations Hu, Sc, So, QR, WR, and, for the foreign language requirement, L1, L2, L3, L4, or L5. (See http://catalog.yale.edu/ycps/yale-college/distributional-requirements/.) Credits earned in courses completed on a Credit/D/Fail basis may not be used to fulfill any of the distributional requirements, nor may credits earned in independent study, tutorial, directed research, or directed reading courses. In addition, acceleration credits may not be applied toward fulfillment of distributional requirements. Thus, the minimum distributional requirement for a student with minimal language proficiency is 9 course credits (2 in the humanities and arts, 2 in the social sciences, 2 in writing, and up to 3 language course credits).

Given that Chemical Engineering students must take courses (as described above) to fulfill distributional requirements, and that many of these courses come from nontechnical subject areas, the broad education component of the Yale undergraduate experience complements the technical content of the Chemical Engineering curriculum. It allows the students to put their engineering work in a broader context, thus being consistent with Program Educational Objective 2: Become ethical professionals who advance chemical engineering practice and knowledge in multiple fields and recognize the local and global impacts of their work on humans and the environment. Furthermore, the nontechnical courses that students take in Humanities, Social Sciences, Writing, and Languages help them to practice and strengthen their oral and written communication skills. Therefore, the broad education component is also consistent with Program Educational Objective 4: Have a strong educational foundation enabling them to study in graduate and professional schools as well as become leaders in STEM or non-STEM career paths.

Major Design Experience that Prepares Students for Engineering Practice:

Chemical Engineering students gain the majority of their design experience in Chemical Engineering Process Design (CENG 416), Chemical Engineering Process Control (CENG 480), and Chemical Engineering Laboratory and Design (CENG 412L). The course with the largest design component is CENG 416, the "capstone design course," which is discussed first.

- Lecture Courses with Chemical Engineering Design Components

  Chemical Engineering Process Design (CENG 416): The senior capstone design experience is contained within the course Chemical Engineering Process Design (CENG 416). The first half of the course involves formal instruction in design and engineering economics of chemical process plants, and it follows the text Plant Design and Economics for Chemical Engineers by Peters, Timmerhaus, and West. Students learn about the design of chemical processes and plants, based on the principles of chemical engineering (as developed throughout the curriculum) and economics (taught primarily in this course). Emphasis is placed on flow-sheet development, equipment selection and sizing, cost estimation, economic analysis, optimization, safety and hazards analysis, and environmental and ethical considerations. Students complete homework in the form of problems and small process simulation projects. The Aspen HYSYS process engineering suite is introduced and used to solve design problems and the capstone design project in Chemical Engineering.

The focus of the course is on the capstone design project, where teams of three to four students propose a design of an assigned chemical process. The key objective is to apply basic science and engineering knowledge learned throughout the curriculum, and the fundamental design knowledge developed in the course, toward a practical design process. Teams are required to take into consideration all financial, environmental, societal, and safety aspects that determine the technical and economic viability of the project. In Academic Year 2019–2020, students in CENG 416 were asked to design a process for producing ethylene from ethane using oxidative dehydrogenation (ODH). A detailed statement of the problem and design constraints (such as the purity of the ethylene produced by the process) is contained in Appendix G. Each team of students developed their own solution to the design problem and submitted a detailed report describing their quantitative solution and engineering-based assessment of the project's technical and economic viability. In addition, each team gave a 30-minute presentation to the Program faculty. The faculty assessed the presentations in terms of attainment of Student Outcomes, as discussed in Chapter 4.

Chemical Engineering Process Control (CENG 480): Students in the Program complete a major individual design project in Chemical Engineering Process Control (CENG 480). Students are required to design and develop a control strategy for a complex chemical engineering process using the theory they learn in the course. The project involves completing background research, performing data analysis, doing linear model development, and testing their control strategy on simulation blocks supplied by the instructor. The students each produce a 10–20 page report detailing their findings and recommendations. In Fall 2019, students in the course each designed a control system for an autothermal reformer for converting methane into hydrogen and water to supply hydrogen for a fuel cell to produce electricity. The challenge was to accommodate the fluctuating demand for hydrogen (i.e., power).

- Laboratory Course with Chemical Engineering Design Components

Chemical Engineering Laboratory and Design (CENG 412L): Several of the experiments conducted in Chemical Engineering Laboratory and Design (CENG 412L) involve a design component. Examples include a distillation process for separating water from ethanol, a reaction process to convert ethyl acetate to acetic acid, and a membrane separation process to separate oxygen from nitrogen (based on an air feed). In each case, certain parameters are explored over the course of an experiment, and based on analysis of results, students recommend a general strategy toward an optimal design.

Cooperative education:

The Chemical Engineering Program at Yale does not allow cooperative education to satisfy curricular requirements.

Materials available for review during the campus visit:

The Chemical Engineering Program will provide the following curricular materials for the review visit: 1) course materials including the syllabus, all assignments and exams and three examples of student work (exemplary, satisfactory, and unsatisfactory); 2) the general institution catalog (i.e., the Yale College Programs of Study); 3) promotional brochures describing the offerings of the School of Engineering & Applied Science; and 4) official academic transcripts of all Program graduates. Additional review materials concerning continuous improvement of Student Outcomes attainment are described in Chapter 4.

B. Course Syllabi

Appendix A includes course syllabi for the required courses, several possible elective courses (from which students select three), and all of the prerequisite courses in mathematics, chemistry, and physics.

CRITERION 6. FACULTY

A. Faculty Qualifications

As of July 2020, the Department of Chemical and Environmental Engineering at Yale consists of 15 full-time faculty members and 2 adjunct faculty members (see Table 6-1 on the next two pages). The Department supports two programs, Chemical Engineering (ChE) and Environmental Engineering (EnvE), each with graduate and undergraduate components. Broken down by program, 9 full-time and 1 adjunct faculty member primarily support the ChE Program. Given the contributions of the Department of Chemical and Environmental Engineering, tabular data are presented for the entire Department.

The faculty cover a broad range of expertise, including reaction engineering, catalysis, transport phenomena, thermodynamics and statistical mechanics, colloid and interfacial phenomena, surface science, nanomaterials, biomaterials, polymers, fuel cells, and photo-synthetic electrochemical devices. A common thread among our research efforts is a focus on processes at interfaces. The faculty is primarily composed of experimentalists, although Profs. Haji-Akbari and Loewenberg are theoreticians, and Prof. Van Tassel combines various levels of modeling with his experimental activities. The overall diversity of skills allows fruitful collaboration on course development.

Chemical Engineering majors at Yale also benefit greatly from course offerings in both Biomedical Engineering (BME), Environmental Engineering (EnvE), and Mechanical Engineering (ME). Many of the core BME faculty have training in chemical engineering. BME course offerings serve to expand educational opportunities for Chemical Engineering students, making them aware of important and exciting new applications of chemical engineering techniques to biomedical problems. EnvE faculty members typically teach courses for the EnvE majors, which provide attractive electives for the ChE students. ME offers many interesting courses that complement the chemical engineering curriculum, including courses on material science and computer-aided design.

The educational backgrounds of our faculty are summarized in Table 6-1 and detailed via individual CVs (Appendix B). All of the faculty members hold Ph.D. degrees. Program Faculty are highly experienced, with significant teaching experience, as shown in Table 6-1. Most have taught at least three of the core undergraduate courses, providing needed flexibility given Yale's triennial and junior faculty leave policies, and serving to keep a fresh teaching perspective. With a few exceptions, courses are rotated among faculty about every three years.

Program Faculty come from a variety of educational backgrounds including training in chemistry, chemical engineering, mechanical engineering, and environmental engineering. Training includes work in industrial settings, academic and governmental research laboratories. These diverse backgrounds enable different perspectives and problem solving tools.

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Table 6-1. Faculty Qualifications.

Chemical Engineering

Faculty Name	Highest Degree Earned, Field, and Year		Rank [1]	Type of Academic Appointment[2] T, TT, NTT	FT or PT[3]	Years of Experience			Professional Registration/ Certification	Level of Activity[4] H, M, or L		
						Govt./Ind. Practice	Teaching	This Institution		Professional Organizations	Professional Development	Consulting/summer work in industry
Eric Altman	Ph.D., Chem. Eng.	1988	P	T	FT	0	26	26		M	H	M
Paul Anastas	Ph.D., Chem. Eng.	1989	A	NTT	FT	18	13	13		M	H	M
Menachem Elimelech	Ph.D., Env. Eng.	1989	P	T	FT	0	31	22		M	H	M
John Fortner (EnvE DUS)	Ph.D., Env. Eng.	2007	ASC	TT	FT	0	10	1		M	H	M
Drew Gentner	Ph.D., Env. Eng.	2012	ASC	TT	FT	0	6	0.5		M	H	M
Peijun Guo	Ph.D., Mat. Sci. & Eng.	2016	AST	TT	FT	0	0	0		M	H	M
Amir Haji-Akbari	Ph.D., Chem. Eng.	2012	AST	TT	FT	0	3	3		M	H	M
Shu Hu	Ph.D., Mat. Sci. & Eng.	2011	AST	TT	FT	0	4	4		M	H	M
Yehia Khalil	Ph.D., Chem. Eng.	1992	A	NTT	PT	18	24	24		M	H	M
Jaehong Kim (Chair)	Ph.D., Env. Eng.	2002	P	T	FT	0	18	7		M	H	M
Michael Loewenberg (ChE DUS)	Ph.D., Chem. Eng.	1988	P	T	FT	0	25	25		M	H	M
Jordan Peccia	Ph.D., Env. Eng.	2000	P	T	FT	0	19	12		M	H	M
Lisa Pfefferle	Ph.D., Chem. Eng.	1984	P	T	FT	0	37	37		M	H	M

T. Kyle Vanderlick	Ph.D., Chem. Eng. 1988	P	T	FT	1	31	12.5		M	H	M
Paul Van Tassel	Ph.D., Chem. Eng. 1993	P	T	FT	0	24	19		M	H	M
Mingjiang Zhong	Ph.D., Chem. 2013	AST	TT	FT	0	4	4		M	H	M
Julie Zimmerman	Ph.D., Env. & Wat. Res. Eng. & Res. Policy & Behav. 2003	P	T	FT	2	15	13		M	H	M

1. Code: P = Professor ASC = Associate Professor AST = Assistant Professor I = Instructor A = Adjunct O = Other
2. Code: TT = Tenure Track T = Tenured NTT = Non Tenure Track FT=Full-time PT=Part-time
3. At the institution
4. The level of activity, high, medium or low, an average over the year prior to the visit plus the two previous years.

B. Faculty Workload

On average, approximately half of faculty effort is committed to teaching and administration and half committed to research. The teaching workload for Academic Year 2019–2020 is shown in Table 6-2 on the next two pages. As is apparent, faculty teach no more than two courses per year.

Tenured faculty are allowed triennial leaves, i.e., one semester free of teaching and administrative duties following every five semesters of teaching. Junior (i.e., tenure-track) faculty members take two full-year leaves during their first eight years at Yale, one as an assistant professor and one as an (untenured) associate professor. The faculty on leave during Academic Year 2019–2020 are indicated in Table 6-2.

C. Faculty Size

As of July 2020, nine ladder faculty members contribute to the Yale Undergraduate Chemical Engineering Program. In Academic Year 2019–2020, they were assisted by one non-ladder faculty, Prof. Khalil.

Given the Program's small faculty size and Yale's generous leave policy discussed above, covering the entire curriculum can be a challenge. In the report following our Self-Study Report in 2014, a concern was raised about the reliance of the Program on a mechanical engineering thermodynamics course (MENG 211) in place of Chemical Engineering Thermodynamics (CENG 300). Fortunately, there have been significant improvements to the Program since 2014.

- Starting in Fall 2015, all students in our Program have taken CENG 300. Since then, our faculty have been teaching all of the required courses, except for MENG 361 (Mechanical Engineering II: Fluid Mechanics), which is taught by our colleagues in ME.

- Starting in Fall 2020, the Chemical Engineering faculty will offer a two-semester transport sequence (CENG 314, 315), obviating the need for our students to take MENG 361. Details of this Program revision is described in Chapter 4. B.

Henceforth, the students in our Program will take all their required core courses in Chemical Engineering.

With a graduating class size of 15–20 students, the student-to-faculty ratio is about 2:1 in our classes. The small student-to-faculty ratio provides an opportunity for significant interaction with undergraduate students. Most of our undergraduates carry out research projects in faculty laboratories, some students take research as a formal engineering elective (CENG 471: Independent Research), while others work in labs for up to three years as part of their work-study program. The research experience can contribute greatly to the overall educational experience: students obtain first-hand experience with research in a university setting and become well acquainted with a professor, who may then offer career guidance and support, including letters of recommendation based on frequent and prolonged associations. These close associations and

Table 6-2. Faculty Workload Summary.

Chemical Engineering

Faculty Member (name)	PT or FT [1]	Classes Taught (Course No./Credit Hrs.)	Term[6]	Year[2]	Program Activity Distribution[3]			% of Time Devoted to the Program[5]
					Teaching	Research or Scholarship	Other[4]	
Eric Altman	FT	CENG 480: Chem. Engineering Process Control	F	2019	50	50		100
	FT	ENAS 602: Chemical Reaction Engineering	SP	2020	50	50		100
Paul Anastas	FT	CHEM 600: Research Seminar	F	2019	50	50		100
	FT	CHEM 600: Research Seminar	SP	2020	50	50		100
Menachem Elimelech	FT	On leave	F	2019		100		100
	FT	ENAS 642: Envir. Physiochemical Proc.	SP	2020	50	50		100
John Fortner (EnvE DUS)	FT	ENAS 638: Envir. Chemistry	F	2019		50	50	100
	FT	ENVE 120: Intro. Environmental Engineering	SP	2020		50	50	100
Drew Gentner	FT	On leave	F	2019		100		100
	FT	On leave	SP	2020		100		100
Amir Haji-Akbari	FT	ENAS 603: Energy Mass & Momentum Proc.	F	2019	50	50		100
	FT	On leave	SP	2020		100		100
Shu Hu	FT	On leave	F	2019		100		100
	FT	ENAS 609: Nanotechnology for Energy	SP	2020	50	50		100
Yehia Khalil	PT	CENG 416: Chem Engineering Process Design	SP	2020	50			50

Jaehong Kim (Chair)	FT	CENG 377: Water Quality Control	F	2019	50	25	25	100
	FT	On leave	SP	2020		75	25	100
Michael Loewenberg (ChE DUS)	FT	ENAS 521: Classical & Stat Thermodynamics	F	2019	50	50		100
	FT	CENG 150: Eng. Improv: Intro. Eng. Analysis	SP	2020	50	50		100
Jordan Peccia	FT	ENAS 641: Biological Processes: Env Eng	F	2019	50	50		100
	FT	ENVE 420: Rethinking Urban Sanitation	SP	2020	50	50		100
Lisa Pfefferle	FT	On leave	F	2019		100		100
	FT	On leave	SP	2020		100		100
T. Kyle Vanderlick	FT	CENG 300: Chemical Eng. Thermodynamics	F	2019	50	50		100
	FT	CENG 315: Transport Phenomena	SP	2020	50	50		100
Paul Van Tassel	FT	CENG 411: Separation & Purification Processes	F	2019	50	50		100
	FT	CENG 412L: Chem Engineering Lab & Design	SP	2020	50	50		100
Mingjiang Zhong	FT	On leave	F	2019		100		100
	FT	Chemical Kinetics and Chemical Reactors	SP	2020	50	50		100
Julie Zimmerman	FT	CHEM 600: Research Seminar	F	2019	50	50		100
	FT	ENAS 360: Green Eng. & Sustainable Design	SP	2020		100		100

1. FT = Full Time Faculty or PT = Part Time Faculty, at the institution
2. For the academic year for which the Self-Study Report is being prepared. (2019–2020)
3. Program activity distribution should be in percent of effort in the program and should total 100%.
4. Indicate sabbatical leave, etc., under "Other."
5. Out of the total time employed at the institution.
6. F = Fall Term, SP = Spring Term

additional learning have significant advantages for the students as they transition to the next phases of their careers following graduation.

Informal contact between faculty and groups of students are facilitated by the small student-to-faculty ratio and are a frequent occurrence. For example, the Yale Student Chapter of the American Institute of Chemical Engineers (AIChE) hosts a few dinners each semester, with least one faculty member invited to each dinner. These meetings are an invaluable opportunity for students to provide feedback on courses and on other aspects of their educational experience, as well as for asking general questions about chemical engineering as a career.

As described in Chapters 1 and 4, the DUS serves as the primary academic advisor for all Chemical Engineering majors and as a liaison between them and instructors in other courses and their Residential College Deans as needed. The DUS meets regularly with students individually and in groups to discuss curricular matters and broader career issues, including summer internships, employment, and graduate school. These meetings provide the DUS with valuable Student Outcomes assessment methods (Assessment Methods 3 and 5, as described in Chapter 4). Although the DUS is the point person for student interactions, most of the faculty members are actively engaged with at least some of the students outside of the classroom through research. Through such mentoring relationships, Program faculty provide additional career counseling.

Students are also advised and supported by their Residential College Deans throughout their four-year program. First-year students have additional support from First-Year Counselors (seniors in their residential college), “Big Sibs” (sophomores in their residential college), and First-Year Academic Advisors (faculty volunteers from Yale College, including ones from our Program). Events early in the academic year, organized by Yale College and the School of Engineering & Applied Science, serve to put prospective engineering majors in contact with Program DUSs.

D. Professional Development

As noted on the CVs supplied in Appendix B, the Chemical Engineering Faculty members are active in research, with most faculty members involving undergraduate students on their research teams. Most of the Program Faculty regularly attend the American Institute of Chemical Engineers (AIChE) Annual Meeting, where they present papers, chair technical sessions, and network with colleagues from academia and industry. Students in the Program are often supported to attend and present their research at the Student Poster Session.

E. Authority and Responsibility of Faculty

Here, the processes involved in course creation or modification, course evaluation, and revision of Program Educational Objectives (PEOs) and Student Outcomes (SOs) are described.

<u>Course Creation or Modification</u>

Faculty are directly involved in the creation and modification of courses. A new course, or a significant modification of an existing course, is either suggested by the individual faculty member planning to teach the course, or by the Program Faculty as a whole. Following discussion and approval by the Program Faculty, proposals for new courses and changes to existing courses are initiated by the instructor of record in the web-based curriculum management tool, CourseLeaf. The DUS is responsible for verifying that the details of the course are accurately described on the web form, describing the importance of the course for the Chemical Engineering Program, and electronically submitting the proposal to Yale College's Course of Study Committee. This Committee reviews the course for consistency with Yale's academic policies, with the Yale College Faculty then voting on changes at monthly faculty meetings. The DUS and Committee iterate on any changes required for the new or altered course to be accepted.

Course Evaluation

In order to assist instructors in improving their courses and their teaching, Yale College encourages students to participate in a college-wide system of anonymous course evaluation for all courses in which they enroll. Students must complete, or actively decline to complete, online evaluations for their courses in order to obtain early access to online reports of term grades from the Registrar's Office. This approach garners a participation rate exceeding 80%.

The feedback provides valuable data for faculty to improve their courses, for Department Chairs to evaluate the teaching of instructors, and for students making course selections. Course evaluation data also provide a valuable additional method of assessing the attainment of Student Outcomes; see the discussion of Assessment Method 4 in Chapter 4.

Assessment of Student Outcomes and Continuous Improvement

Although financial and infrastructural support are provided by the Offices of the Dean and Provost, the direction of the Program is at the discretion of the Chemical Engineering Faculty. Program Faculty are responsible for continuously improving Yale's Chemical Engineering Program, and they have the authority to implement improvements.

The Program Faculty play a critical role in attaining SOs, as described in Chapter 4. The Program relies on six methods to assess the attainment of Student Outcomes including a course-based Student Outcomes assessment method, "The Yale Method" (Assessment Method 1 in Chapter 4). This method is embedded in a user-friendly Excel spreadsheet, where faculty use their own grading system to track results of student performance. In this spreadsheet, faculty input grades for each assignment (exams, homework, and other coursework), and assign a corresponding weighting factor and a fractional component to each of the Student Outcomes associated with each particular assignment.

This spreadsheet also yields the breakdown of student performance (unsatisfactory, acceptable, and exemplary) per assignment based on the faculty's input for the cutoff percentages. The spreadsheet then calculates a grade for each student and the percent of each ABET Student Outcome that is achieved by this course. Finally, the spreadsheet produces a graph and a table that clearly shows the levels of performance for each ABET outcome that is assessed in the course. The analysis of each single course is readily aggregated with other courses in the curriculum to establish an overall measure of the attainment of each SO. These results show the contributions at the course and program levels for each SO to quantify the range of performance and serve as a tool for continuous improvement.

The other five Assessment Methods (AMs) described in Chapter 4 are faculty reviews of the capstone design presentations (AM 2), individual meetings and anonymous surveys of students in the program (AM 3, 4), exit interviews and surveys of graduating seniors (AM 5), and surveys of recent alumni (AM 6). Collectively these methods provide reliable monitoring of Student Outcomes attainment by graduates from our Program.

Chapter 4.B describes several examples of problems that were identified by a combination of these assessment methods and the Program revisions that were implemented to address them.

Revision of Program Educational Objectives and Student Outcomes

The process involved in deciding whether to create new or modify existing courses, PEOs, and SOs involves a cooperative decision-making process that includes several constituencies. The decision-making process for revising the PEOs was described in detail in Chapter 2.E. A similar process is carried out when determining whether SOs should be added or changed. Currently, the Program adopts the ABET Student Outcomes 1–7.

Once a decision has been made to change the PEOs or SOs, the DUS requests that the appropriate changes be made in the Yale College Programs of Study (YCPS) and on the Chemical Engineering website. Changes made in the YCPS automatically propagate to the Yale Course Search website (courses.yale.edu).

CRITERION 7. FACILITIES

A. Offices, Classrooms and Laboratories

<u>Offices for administration, faculty, clerical and teaching assistants</u>

Not only has the School of Engineering & Applied Science (SEAS) succeeded in attracting top faculty, but it also seeks only the best in research, administrative, and technical staff — all dedicated to furthering the excellence of the research and teaching in SEAS. The SEAS Dean's Office is located in "17 Hillhouse" Room 105. Its staff is composed of 14 employees (including the Dean, Deputy Dean, and Assistant Dean), all working together to support students and faculty in their academic affairs. They coordinate School-wide functions such as communications and admissions, assist undergraduate students with their extra-curricular activities (e.g. undergraduate student groups), provide financial support and financial administration, and guide students concerning safety and content relevant to projects associated with their academic paths.

Professors Haji-Akbari, Loewenberg, Pfefferle, and Van Tassel have office and lab space in Mason Lab. Professor Altman has office and lab space in the Malone Engineering Center, Professor Zhong has office and lab space in 17 Hillhouse, and Professor Vanderlick has an office in Dunham Lab and lab space in 17 Hillhouse. Professors Hu and Guo each have lab space and an office on the West Campus and another office in Mason Lab because of the interdisciplinary nature of their research.

The Department of Chemical and Environmental Engineering is supported by two administrative assistants. Ben McManus is located in Mason Laboratory Room 300, and Molly McKenna is located in 17 Hillhouse Room 530. These individuals assist in supporting the Faculty's administrative needs, including academic recordkeeping and student payroll (for Program students working at Yale). The offices of the administrative assistants are equipped with fax machines, copiers, and scanners for faculty use. In addition, there is a color HP plotter printer in the common area of the Dean's Office for faculty and students to print posters for projects, activities, and presentations.

Teaching Fellows for undergraduate courses are provided with workspace associated with their research laboratories. While some of the spaces are within the laboratories, the majority are external offices that house a number of graduate students.

In addition to SEAS resources, engineering faculty have access to Yale-wide resources to advance teaching skills. Yale established the Poorvu Center for Teaching and Learning in 2017 to improve teaching, support engaged learning, and centrally locate education resources and support for the Yale community. As a modern, open, and inviting 24,000-square-foot facility, the Center has flourished as the university's preeminent hub for teaching and learning and represents a new era in Yale's commitment to pedagogical excellence. Of note was the very central role this

Center played in the abrupt transition to remote learning during the Spring 2020 semester, as well as the important guidance the Center's staff is providing to help faculty plan, facilitate and deliver online content in future courses.

Two other Yale University facility investments deserve to be noted for their magnitude, proximity, and effect on Yale's engineering program. The Tsai Center for Innovative Thinking at Yale (Tsai CITY) will open in September 2020 and will serve, in partnership with two School of Engineering & Applied Science venues, as "Yale's Innovation Corridor." Tsai CITY is an independent center that fosters innovation, entrepreneurship, and problem solving for Yale students. Housed in a new 10,000-square-foot building in the middle of Yale's engineering campus, staffed with 16 employees, and under the operational/organizational structure of the Provost's Office, Tsai CITY provides co-curricular and extra-curricular support to students who form teams, partnerships, and ventures to apply innovation, entrepreneurship, and leadership skills to solve problems and create change. While not all problems have a technology focus, the establishment of Tsai CITY on the engineering campus greatly benefits engineering students develop these aspects of their professional and personal pursuits.

In a similar vein, though not an engineering facility, the Schwarzman Center will open in Fall 2020 as a center for student life and the arts at Yale. Designed to draw together students, faculty, and alumni from all of Yale's schools and colleges, the Schwarzman Center is open to all at Yale and provides spaces for meeting, dining, and networking. In addition to these functions, the Center will serve as a venue for thought-provoking cultural programs throughout the year. Of note is the fact that the Schwarzman Center adjoins the engineering campus, with its location and openness thereby being of immediate benefit for engineering students. They will be able to use the Center for curricular and extracurricular uses such as problem set gatherings, lab group discussions, and engineering club meetings.

General purpose classrooms within the Yale School of Engineering & Applied Science

Yale College maintains classrooms throughout the campus to which SEAS has access as needed. Classrooms for which SEAS has direct control include two 20-seat classrooms (Becton Engineering Center Room 408 and Becton Engineering Center Room 508), a 25-seat classroom (Arthur K. Watson Hall Room 200), and one 20-seat seminar room (Mason Laboratory Room 107). Classrooms under the control of the Yale Registrar that are located in SEAS buildings include a 260-seat auditorium (Davies Auditorium in the Becton Engineering Center), a 100-seat classroom (Mason Laboratory Room 211), a 150-seat classroom (Dunham Laboratory Room 220), a 45-seat classroom (Becton Engineering Center Room CO31), a 30-seat classroom (Mason Laboratory Room 104), and a 25-seat classroom (Arthur K. Watson Hall Room 100). A 21-station computer classroom is located in Dunham Laboratory 120D, and a 52-station computer classroom is located in 17 Hillhouse.

Unique classrooms accessible to the Yale School of Engineering & Applied Science: Classrooms located in 17 Hillhouse

Six classrooms are located in the building that is officially called 17 Hillhouse (in the midst of the Yale SEAS concentration of buildings on Yale's campus bounded by Prospect St., Trumbull St., Hillhouse Ave., and Grove St.). This building was renovated in 2013 to improve and advance science and technology education at Yale. The building renovation converted the former medical facility into a modern teaching and research center, with classrooms, research laboratories, and faculty and student offices all housed in this building. The 17 Hillhouse classrooms encourage discussion and interaction among students in smaller classes and lectures alike, and include a 126-seat Technology Enabled Active Learning (TEAL) classroom where students sit at 9-person tables in a technology-rich environment. This classroom promotes active learning and enables technology (from the instructor and from each student) to be integrated into the lectures, demonstrations, and discussions. Some of the chemical engineering courses are held in 17 Hillhouse classrooms.

Unique learning environments accessible to the Yale School of Engineering & Applied Science: Center for Engineering Innovation and Design (CEID)

Yale's Center for Engineering Innovation and Design (CEID) in the Becton Engineering Center helps catalyze Yale's design, innovation, and creativity initiatives. In operation since 2012, the CEID serves not only our own students but also the entire design community at Yale. The CEID's mission is to "empower its members to improve human lives through the advancement of technology. CEID aspires to launch high-impact projects and develop visionary leaders. It does so by bringing together people from diverse backgrounds and giving them resources to learn, create, and share."

Membership in the CEID provides 24/7 access to a functional facility that includes an open studio, workshops, meeting rooms, and an instructional area. Membership is open to all students, faculty, and staff at Yale. The studio is equipped with 3D printers, hand tools, electronics fabrication and testing equipment, and a variety of materials and components available to members at no charge. CEID members also have access to a state-of-the-art machine and metal shop, wood shop, and wet lab, as well as the assistance of four staff members (two Ph.D.-level, two B.S.-level) that manage all aspects of the CEID. The Director of the CEID is Deputy Dean Vincent Wilczynski, who devotes half of his time to this role.

The CEID sponsors a spectrum of formal and student-driven activities to educate its members, build community, catalyze new creative ventures, and support member-driven projects. CEID staff regularly teach academic courses including a hands-on freshman engineering course (ENAS 118), a course on the design of new products (ENAS 400), and a course on the design of musical instruments (ENAS 344). In addition, engineering faculty regularly team-teach design courses in the CEID on sustainable design (ENAS 360, co-taught by Environmental Engineering and Chemistry faculty) and the design of biomedical devices (MENG 404/BENG 404, co-taught by Mechanical Engineering and Biomedical Engineering faculty). Beyond for-credit courses, CEID staff train students to use the facility's 3D printers, laser cutter, and machine tools.

In addition to this formal instruction, the CEID annually hosts more than 30 workshops on a variety of topics, such as building websites, making mathematical artwork with 3D printers, assembling electronic circuits, creating engineering portfolios, and microprocessor-based programming. The CEID also hosts lectures where speakers share their experiences in engineering, innovation, and design to inspire new projects, understand new trends in technology and the marketplace, and highlight potential career paths. In addition to these activities, the CEID regularly hosts social events to encourage networking and to foster a spirit of community, with these events including daily teas, evening study breaks, and an annual kick-off party to mark the start of a new academic year. (See Appendix E for the schedule of events for Academic Year 2019–2020.)

The CEID sponsors a summer fellowship program to support undergraduates in pursuit of their own design ideas. Fellows reside in the CEID for 10 weeks and receive mentoring and technical support from CEID staff in addition to stipends and professional development. The CEID is also a hub for student extracurricular activities. As examples, the Yale chapters of Design for America and Engineers Without Borders, the Yale Undergraduate Aerospace Association, and a number of student groups focused on robotics all use the CEID as their base of operation. The CEID is also a popular student destination for collaboration on class work, with students regularly meeting there to work on problem sets, study, and prepare for exams.

The CEID staff actively collaborate with similar makerspace staff at other universities, both formally through the Higher Education Makerspace Initiative (a partnership of 8 universities who identify, vet, and disseminate best practices related to academic making) and informally with faculty and staff at other academic makerspaces. In October 2019, the CEID hosted the International Symposium on Academic Makerspaces to bring 350 members (from around the world) of this professional society together for three days of workshops, technical discussions, and fellowship.

<u>Unique classrooms accessible to the Yale School of Engineering & Applied Science: CEID instructional area and meeting rooms</u>

The CEID "instructional area" adjoins the open studio, with this instructional area serving four functions. Its first function is to hold classes. During Academic Year 2019–2020, classes held in the CEID instructional area included Making It: Product Design and Entrepreneurship (ENAS 400), Medical Device Design and Innovation (MENG 404/BENG 404), Introduction to Engineering Innovation and Design (ENAS 118), Musical Acoustics and Instrument Design (ENAS 344), and Green Engineering and Sustainable Design (ENAS 360). The openness of the instructional area in proximity to the studio space makes it an excellent venue for design courses, where students can learn the lecture material and readily put it into practice in the studio space.

The second function of the CEID instructional area is to serve as a space for guest lecture series and employment networking gatherings, typically scheduled on Monday evenings. The third use of this area is for CEID Workshop nights. Every Wednesday evening, the CEID staff has a workshop to enable students to explore and apply their creativity and academic knowledge for practical uses. The fourth use of the instructional area is for all other activities, such as student group meetings, social events, occasional symposia, and more. Any member can reserve the space, and it is available 24/7 with ID card swipe access for CEID members.

In addition to the instructional area, there are five reconfigurable conference rooms located on the mezzanine, each containing a computer with a large LCD screen and teleconference capabilities, along with plenty of whiteboard space. These rooms can also be used for classes in addition to meetings, small group discussions, student groups, and study time. The spaces can also be reserved online and are available 24/7 as well.

Teaching Labs and Workshops relevant to the Yale Chemical Engineering Program:
Greenberg Engineering Teaching Co ncourse

Chemical Engineering Laboratory and Design (CENG 412L) is held in the Linda and Glenn H. Greenberg Engineering Teaching Concourse. The Teaching Concourse opened in 2017 as a central undergraduate teaching lab facility for all engineering majors. Spanning 10,000 square feet, the facility includes eight labs in total, including two wet labs with ventilation hoods and a tissue culture room. In addition, the concourse contains large lab preparation and storage rooms where course experiments can be developed in advance and wheeled into the labs at the appropriate point in the semester. The space also includes an office for the School's Research and Teaching Support Staff: Mechanical Engineering Design Advisor Glenn Weston-Murphy, Electrical Engineering Design Advisor Kevin Ryan, and Research Scientist Katherine Schilling (Ph.D. in Chemistry).

The Teaching Concourse includes a single wide hallway that connects the floor-to-ceiling glass walled labs (and the staff office) along both sides of the hallway. The openness and visibility of the space is intentional to promote learning, awareness, and safety. By centralizing engineering labs into one space, the Teaching Concourse encourages collaboration between students and faculty across all disciplines within engineering. A walk through the Teaching Concourse during lab instruction periods provides a window into each engineering discipline, thanks to the high visibility within the space. The facilities are exclusively used for academic courses.

Six dry labs range from 700 to 1,300 square feet and accommodate between 16 and 24 students in each lab with two students per lab station. Three of the labs are separated by folding doors (all of which are white-boards) to enable these three labs to be used in alternate configurations. Three of the dry labs are outfitted with advanced electronics stations (computer, oscilloscope, power supply, function generator, and support tools), while two other wet labs are equipped with the same collection of electronics (though at a more basic functional level). The fifth dry lab has a single electronics station to support periodic needs, with the lab workbenches generally left open to accommodate open-ended project courses and general lab instruction. Two wet labs are 550 and 650 square feet, with each lab having two hoods and a sink (including de-ionized water supply). One of the wet labs includes the tissue culture space. The wet labs can accommodate between 6 and 12 students, with these lab spaces used in tandem with a dry lab for course instruction.

CENG 412L is typically taught in a combination of two labs — a dry lab and a wet lab — with lab apparatus located in each room and the dry lab also serving as an instructional space for lab theory. The two labs are located across the hall from each other, separated by floor-to-ceiling glass enclosures, giving the lab visual continuity while containing operations that need to be conducted in a wet lab (which includes hoods).

Intentionally so, the labs are managed, scheduled and staffed centrally by the SEAS Teaching Support staff to increase space utilization within the concourse. While specific lab assignments can change each semester, it is not uncommon for a particular lab to house multiple disciplines in a single semester, thereby helping meet the multidisciplinary intentions for the space. This $10M infrastructure investment, accompanied by outfitting the labs with $750K of new equipment including 72 new computers, electronics, experiment stations, and fabrication tools, demonstrate Yale's significant commitment of resources to support undergraduate engineering education.

Teaching Labs and Workshops relevant to the Yale Chemical Engineering Program:
SEAS Machine Shop

The School of Engineering and Applied Science maintains other teaching labs that support all departments at SEAS. One such space is the SEAS Machine Shop, which assists students, staff, and faculty conceive, design, and construct apparatus and instrumentation for the support of research and instructional projects. The SEAS Machine Shop Director Nick Bernardo has more than 25 years of diverse industrial and academic machining and fabrication experience. His expertise includes prototyping and CNC machining. He advises and assists students, staff, and faculty through individual and group instruction. He also provides constant safety oversight of all work in the shop. Equipment in the SEAS Machine Shop is detailed in Table 7-1.

Table 7-1. List of Equipment in the SEAS Machine Shop.

SEAS Machine Shop Equipment	**Quantity**	**Description**
Haas Toolroom TL 1	1	CNC lathe
Clausing 600-group 13-inch lathes	2	Lathe
Sharp 1118H	1	Precision lathe
Jet GH-1640ZX	1	Precision lathe
Acer E-mill 3VS	3	Milling machine
Sharp precision CNC milling machine	2	CNC milling machine
Jet 20-inch band saw	1	Band saw
Wilton 6-inch belt sander	1	Belt sander
Baldor 2-inch belt sander	1	Belt sander
Baldor pedestal grinder	1	Pedestal grinder
Lincoln power mig welder	1	Metal inert gas welder
ProtoMax by Omax	1	Waterjet cutter
Dayton drill press	1	Drill press
MSC drill press	1	Drill press
Powermatic drill press	1	Drill press
Trinco dry blast sand blaster	1	Sand blaster
DI-ACRO sheet metal brake	1	Sheet metal brake

DI-ACRO sheet metal sheer	1	Sheet metal shear
Rotex sheet metal hole punch	1	Sheet metal hole punch
DI-ACRO sheet metal pinch roller	1	Sheet metal pinch roller

Teaching Labs and Workshops relevant to the Yale Chemical Engineering Program:
CEID "Laboratory Spaces"

As mentioned briefly earlier, the CEID is composed of a number of stations that are used for hands-on activities associated with courses, undergraduate research and projects, and student organizations. The CEID is divided in four major spaces in addition to its instructional area: Studio (including the Electronics Stations), Machine and Metal Shop, Wood Shop, and Wet Lab. These spaces are described below.

The **CEID Studio** is a space with several stations equipped with 3-D printers, hand-tools, electronics fabrication and testing equipment, and a variety of materials and components available to members at no charge. A list of equipment is presented in Table 7-2. Note that the equipment in the CEID Electronics Stations is listed separately after the table.

Table 7-2. List of Equipment in CEID Studio.

Equipment	**Quantity**	**Description**
Aticio MP C300	1	Printer
Camm-1 Servo	1	Vinyl cutter
Dell	5	Computer
Mac	2	Computer
Objet 30 Pro	1	3D printer
Stratasys F270	1	3D printer
Makerbot Replicator	1	3D printer
Makerbot Replicator 2	1	3D printer
Makerbot Replicator 2x	1	3D printer
Milwaukee 3.8" Right Angle Drill	1	Right angle drill
Milwaukee M18 Red Lithium	2	18 volt impact driver
M18 Red Lithium Drill	3	Drill
Milwaukee HackZall	1	Reciprocating saw
Milwaukee Jig Saw	1	Jig saw
Dremel 4000	2	Dremel tool
Janome Model HD-1000	1	Sewing machine
Canon EOS Rebel T3i	1	Camera

Located within the CEID Studio, the **CEID Electronics Stations** (2 stations) each have the equipment in the list below. Each station gives students the capability to assemble prototype circuits on breadboards and PC boards, and to evaluate, test, and debug the circuits using a variety of diagnostic equipment.

- Techtronix TBS 2000 Series Digital Oscilloscope
- Techtronix AFG1022 Function Generator
- Keithley 2231A-30-3 Triple Channel DC Power Supply
- Weller WES51 Soldering Iron
- Weller WSA350 Smoke Absorber
- Panavise Circuit Board Vise
- Aoyue Int 2702A Repairing System for soldering/de-soldering
- Fluke 179 True RMS Multimeter
- HP 973A Multimeter
- Prototyping Breadboards
- Arduino hardware
- Electronics components (resistors, capacitors, transistors, op amps, LEDs, servos, sensors, etc.)

The **CEID Machine and Metal Shop** and the **CEID Wood Shop** are accessible to students only with staff supervision. Students can use this space for projects, personal design pursuits, and classes. Available tools and equipment are given in Tables 7-3 and 7-4.

Table 7-3. List of equipment in the CEID Machine and Metal Shop.

Machine and Metal Shop Equipment	Quantity	Description
ULS Laser Cutter 4’ × 2’	1	Laser cutter
Tormach PCNC 440	1	CNC mill
Jet VBS-2012	1	Vertical band saw
Jet Beltsander	1	Belt sander
Jet JDP-12	1	Drill press
Jet AP-3	1	3-ton arbor press
Dayton 2XUVS	1	Hand tipper
Jet J-A5816	1	Drill press
Jet JBG-8A	1	Bench grinder
Jet J-4206A	1	Belt sander
Clausing EUS 08	2	Milling machine
Clausing M300	2	Lathe
DI-ACRO Model No. 12SR	1	Slip roller
DI-ACRO Model No. 24 Finger Brake	1	Bender
Tin Knocker	1	Hand turret punch
DI-ACRO Model No. 24HS	1	Shear
DI-ACRO Model No. O2TN	1	Notching machine

Table 7-4. List of equipment in the CEID Wood Shop.

Wood Shop Equipment	Quantity	Description
Shopbot PRS Alpha	1	4’ × 4’ CNC milling/routing
ShopBot Desktop	1	2’ × 1.5’ CNC milling/routing
Jet JBOS-5	1	Oscillating spindle sander
Formech DT508	1	Thermoformer
Labconco	1	Fume hood
Jet JMS-10SCMS	1	Sliding compound miter saw

The **CEID Wet Lab** has equipment that is designed to serve a variety of purposes. One purpose is to facilitate genetic engineering techniques using E. coli. Polymerase reactions may be run and the results may be analyzed using spectroscopic techniques and electrophoresis. Equipment includes but is not limited to: microscopes, transilluminator, vortex mixer, centrifuge, incubator, etc. A second purpose is to support work in microfluidics, including both the standard variety using PDMS (polydimethylsiloxane) molds as well as paper microfluidics more suited to diagnostics for the developing world. Equipment for this purpose includes, but is not limited to: vacuum pump and desiccator, microscopes, fiber optic illuminators, and a fume hood. A third purpose is to house instruments that are used to remove support material from parts produced by CEID 3D printers.

<u>Science education undergraduate teaching labs used by Yale School of Engineering students</u>

In 2017 Yale opened state-of-the-art undergraduate teaching labs for five Yale science departments: Molecular Biophysics & Biochemistry; Molecular, Cellular, & Developmental Biology; Ecology & Evolutionary Biology; Chemistry; and Physics. Located in the Sterling Chemistry Lab, the science teaching lab renovations encompass 159,000 square feet, which include 31,600 square feet of additional space. The renovation project included the new teaching labs, an overhaul of mechanical systems, and new lounge areas and student lockers. These teaching labs are used by engineering students for lab courses in chemistry and physics. These improvements demonstrate Yale’s continued investment in undergraduate educational facilities.

B. Computing Resources

SEAS and Yale College have a variety of computing resources throughout campus available for all students and faculty for academic purposes. The diverse range of classrooms facilitates a productive teaching education experience. From computers to whiteboards, projectors, and printers, to comfortable seating, appropriate lighting, and easy access, these facilities are ideal for the support of scholarly and professional activities for the Chemical Engineering Program.

In the computer resource center in Dunham Laboratory Room 120, students have access to a variety of spaces with computing resources. This computer lab is available 7 days a week, 24 hours/day with key card access. There are 16 general access computers in this room. The room also has a printer station and an adjoining computer classroom (Room 120 D with 21 computers), which is accessible when not being used for instruction.

The networked computers in Dunham Laboratory Room 120 (as well as 17 Hillhouse and in the CEID) are all outfitted with the following software: ANSYS, SolidWorks, MATLAB, IBM SPSS Statistics Data Editor, Minitab 16 Statistical Software, SketchUp, State SE 13.0, Mathematica, DNR GPS, and Aspen HYSYS. In addition, LabVIEW, Origin, Microwave Office, COSMOL Multiphysics, and Ansoft HFSS & Maxwell 3D are available for course and research projects via the Yale Software Library and supported by Mikhael Guy from Yale's Science Research Software Core.

Among the six classrooms in 17 Hillhouse are three computer classrooms. These classrooms were designed to encourage discussion and interaction among students in smaller classes and lectures alike, mainly by replacing formerly stationary furniture with mobile tables and chairs. These rooms also include double-screen video projectors. All rooms are accessible 24/7 with a Yale ID card.

As previously mentioned, the Technology Enabled Active Learning (TEAL) Classroom 101 in 17 Hillhouse seats 126 students at small round tables with computers available at each table. Each table is connected to a video projector, allowing all groups to display their work to the entire class simultaneously on projection screens that line the walls. Equipment includes: annotation monitor (digital notes, annotation), Blu-ray player, document camera, DVD player, microphones (podium and lavaliere), plasma or LCD screens, projectors, and whiteboards.

Classroom 111 in 17 Hillhouse seats 52 students, with a computer station for each (PCs). There are 8 projectors (data and video capable), a DVD player, Blu-ray, a projector (HD 1920×1080), and whiteboards. This room is ideal for a classroom setting.

The Library Computer Classroom 07 in 17 Hillhouse is designed for lectures, presentations, and research. The classroom features 16 PC workstations with standard software. Outfitted with a podium and projectors, the classroom is an ideal space for holding lectures and presentations. Study tables with additional seating for 10 and whiteboards are available for individual or group study and research. The room also houses a printer/scanner/copier.

Arthur K. Watson Hall also contains a 38-station computer facility known as the Zoo, which is located on the third floor of the building. The facility is adjacent to a lounge and eating area, and is open 24/7. At the start of each semester, login accounts on the computers in the Zoo are set up for students taking computer science classes.

Beyond these engineering stations, Yale's Academic Computing Services supports hundreds of public computers that are located throughout campus and are intended for use by members of the Yale community. The computers have a common software image to provide ample access to academic software. Technical help with computing ranging from network connectivity to software installation can be obtained by contacting Yale Information Technology Services (ITS) Helpdesk via phone or email. Their automated ticket and scheduling system ensures that all issues are resolved promptly.

Undergraduates engaged in computational research in the Chemical Engineering Program can also access Yale's significant high performance computing (HPC) facilities that are housed in the West Campus Data Center. Yale Faculty of Arts & Sciences (FAS) HPC operates two clusters. The Omega cluster includes over 8,500 Intel processors (cores), 12 GPU accelerators, and a 1.4-petabyte parallel file system, which makes it well suited to highly parallel work in a variety of fields including the physical sciences and engineering. The Grace cluster provides Yale with an additional 1,440 of the most modern Intel processors along with another petabyte of high-performance storage. Because the Grace cluster includes nodes with 20 cores and 128 gigabytes of memory each, it is especially appropriate for computations that require large amounts of memory and use multithreaded applications.

The University provides a user support staff through the Yale Center for Research Computing comprising six individuals with HPC and scientific computing expertise. The support staff, with an aggregate of over 125 person-years of HPC experience, assists users in developing applications and making effective use of the HPC clusters through its training and consultation activities. Potential undergraduate users can obtain login accounts through faculty research or course sponsors.

C. Guidance

Classroom & Computer Labs Guidance

The Chemical Engineering Program Faculty, staff, and teaching assistants guide students regarding use of laboratory equipment and computer resources. The professor teaching Chemical Engineering Laboratory and Design (CENG 412L), along with the associated Teaching Fellows (Ph.D. students serving as lab assistants), instruct students on the safe and proper use of equipment in the Greenberg Engineering Teaching Concourse. The Program Faculty also instruct students on the availability and use of software needed throughout the curriculum. For example, the professor of Chemical Engineering Process Design (CENG 416) gives at least two lectures on the application of the chemical process simulation software Aspen HYSYS in Dunham Lab 120, equipped with computers and a video projection system. Based on these lectures, students are able to use this software tool for HYSYS simulation exercises and the capstone design project.

SEAS Machine Shop, Design/Electrical Laboratory Guidance

Three full-time teaching support staff train and supervise students for all shop and laboratory activities, with an additional half-time employee providing support for chemical-based learning. Students are instructed in all safety guidelines prior to entering the laboratory, and appropriate signage is clearly posted. Students are guided and supervised as necessary for all laboratory activities to ensure learning and safe operating procedures.

Staff members are active participants who provide professional technical support for research and educational projects. They also serve as a resource for students in career counseling, advising, and networking. In addition to helping students, the staff also works closely with faculty on curriculum improvements, equipment assessment, and any other related topics to ensure the course objectives and student outcomes are being met.

CEID Guidance

To become a member of the CEID and use the tools and the shops it has to offer, students (and also staff and faculty) must participate in an initial orientation before they can use the space. This orientation covers emergency procedures and safety guidelines, such as personal protective equipment (eye wash, fire extinguisher use, safety glasses, etc.). In addition, there are formal trainings for the Machine and Metal Shop, Wood Shop, and 3D printers. Staff members (2 Ph.D.-level, 2 B.S.-level) are available full time from 9:00 am to 6:00 pm, and undergraduate staff is available from 6:00 pm to 9:00 pm. Access to the Machine and Metal Shop, Wood Shop, and Wet Lab is limited to staff only, and students are only allowed under their supervision and following extensive training.

D. Maintenance and Upgrading of Facilities

All computer resources are updated through Yale ITS, which monitors the computers remotely and upgrades them periodically.

For the facilities that are under the control of the Chemical Engineering Program, the Program Faculty maintain and periodically upgrade laboratory equipment and computer resources. As needed, the SEAS teaching support staff can also assist with the equipment maintenance and preparation for use. Each year, the Yale Provost's Office requests proposals for teaching lab equipment. Through this mechanism, the Program added a distillation column experiment (Pignat DVI/3000) in the 2017–2018 academic year, and a chemical reaction experiment (Pignat RAP/4000) in the 2019–2020 academic year. Each serves as one of the six experiments performed by students taking the (ABET-required) CENG 412L course, and also are occasionally used as demonstrations for certain non-lab courses. For example, the distillation column was used in Separation and Purification Processes (CENG 411) during Fall 2018 and Fall 2019. The SEAS Dean's Office also supports the purchase and upgrade of software, e.g., ProSimPlus and Aspen HYSYS for chemical process simulation.

For the CEID, the equipment is checked and tested regularly by CEID staff to ensure safe and proper performance. In addition, annual service contracts are in place for high capital cost equipment. Tools are replaced on an as-needed basis as they wear out. Computing resources are monitored remotely, upgraded, and maintained by Yale ITS, and disk image software is upgraded annually. For the SEAS Machine and Metal Shop, all equipment is checked, tested, and maintained by the shop supervisor.

E. Library Services

The Yale University Library supports and enhances research, teaching, and learning. As part of this mission, the Library provides access to a collection of 15 million print and electronic items in formats including books, journals, and databases. The program is served by a professional librarian who is embedded in SEAS to respond to purchase requests, manage collections, teach information skills, and provide research services.

Service is the top priority, and the engineering librarian consults with faculty members to conduct course-related research education. During Academic Year 2019–2020, the engineering librarian conducted 24 orientation and instruction sessions with 380 participants. In addition, library professional staff offer support and training for citation management, geographic information systems, and statistics and data management.

SEAS students and faculty take advantage of a wide range of research resources and services provided by the 15 libraries and 600 staff comprising one of the largest library collections in the world. The engineering collections are located in the central campus library, which is Sterling Memorial Library. Science materials are also housed in the newly renovated Marx Science and Social Science Library, which includes collections in physics, biology, chemistry, and geology; the Mathematics Library; and the Medical Library. The Yale Library is a U.S. government and United Nations depository. Course reserves and e-reserves are provided and integrated with Yale's course management system.

Access to collections is available during the academic term for as many as 17.5 hours per day at the Bass Library. Study space is provided 24 hours per day at the Marx Science and Social Science Library. A variety of learning/study spaces are available in campus libraries including individual carrels, tables, and group study rooms. Technology tools and services include workstations with internet access, productivity software, data manipulation software, mapping and GIS, presentation preparation, multimedia production, videoconferencing, printing, and scanning.

Students and faculty are provided many resources online via the Yale Library website for ease of access around the clock and around the world. The Library provides online access to thousands of databases for locating research articles, including Web of Science, Engineering Village/Compendex, Inspec, Chemical Abstracts/SciFinder Scholar, and the IEEE Electronic Library. The "Yale Links" resolver connects citations in these databases to full-text sources available to the Yale community. Researchers have access to more than 470,000 journals including major science and technology online periodical packages published by Elsevier Science Direct, Wiley, Springer, Oxford, IEEE, Association for Computing Machinery, American Chemical Society, American Physical Society, the American Society of Mechanical Engineers, as well as many other publishers and societies.

E-books are part of the collection and supplement the strong print collections in science and technology. Yale users have online access to important collections of engineering reference handbooks through AccessEngineering, Knovel, and CRC, including the CRC Handbook of

Chemistry and Physics, Perry's Chemical Engineers' Handbook, and Marks' Standard Handbook for Mechanical Engineers. Other online book subscriptions include major collections for engineering and chemical data, computing manuals, and academic texts.

Materials needed for research may be requested for purchase or through the Library's document delivery services. Articles and book chapters from items in the collection are available for scanning and electronic delivery in 1–2 business days. The Yale Library has partnered with major research libraries to offer the Borrow Direct system that allows books not available locally to be sent on loan within four business days. In addition, Yale provides interlibrary loan borrowing for books and online delivery of articles not available locally. Faculty and students can connect to library services remotely via a VPN client.

F. Overall Comments on Facilities

Program Faculty work with Yale's Office of Environmental Health & Safety (EHS) to ensure that all instructional equipment conforms to University safety standards. A representative from SEAS sits on Yale's Laboratory Safety Committee, and a staff member from EHS is specifically assigned to monitor safety and training in the SEAS laboratories and workshops. In addition, all undergraduates working in research at Yale during the summer must register through an online health and safety management system, EHS Integrator, which ensures that undergraduates received necessary training and faculty abide by the appropriate safety and mentoring standards. Collectively the Faculty, teaching support staff, students, and EHS all work together to ensure the safety of Yale's facilities.

CRITERION 8. INSTITUTIONAL SUPPORT

A. Leadership

The Department of Chemical and Environmental Engineering is led by a Chair, who presides over all departmental matters, two Directors of Undergraduate Study (DUS), who preside over undergraduate affairs (one for the Chemical Engineering Program, and one for the Environmental Engineering Program), and a Director of Graduate Study (DGS), who presides over graduate affairs. Major decisions, such as curricular changes, are made by the Program Faculty via majority vote. Minor decisions are often made directly by the Chair, DUSes, or DGS. The DUS has the authority to grant course substitutions to students, but often consults other Program Faculty before doing so.

The Chair is appointed by the Yale President, following consultation with departmental and possibly other faculty. The term of the appointment is three years. The Chair then appoints the DUSs and the DGS, following consultation of the departmental faculty. The DUS and DGS appointments are reconfirmed annually but usually these positions are held for several years.

Yale's School of Engineering & Applied Science (SEAS) is led by a Dean, who presides over the School. The SEAS Dean works directly with the Provost and Dean of the Faculty of Arts and Sciences (FAS) on administrative matters related to the School of Engineering & Applied Science. The Provost is Yale's chief educational and administrative officer after the President. The Office of the Provost oversees academic policies and activities university-wide. The FAS Dean's Office oversees faculty searches, recruitment, hiring, mentoring, promotions, retentions, and compensation for all ladder, instructional, and research faculty in the Faculty of Arts and Sciences, as well as departmental staffing, budgeting, strategic planning, and policies and practices throughout the FAS.

The SEAS Dean also partners with the Dean of Yale College (Yale's undergraduate program) and the Dean of the Graduate School of Arts and Sciences on teaching and research initiatives. The Department's DUS and DGS are the primary points of contact with Yale College and the Graduate School, with the SEAS Dean's Office providing oversight and School-wide coordination. The Yale Faculty Handbook (http://provost.yale.edu/faculty-handbook) details many of the issues related to faculty governance and operations.

B. Program Budget and Financial Support

Yale University provides a general appropriation fund for operations in the Department of Chemical and Environmental Engineering. Additional funds are made available from discretionary accounts within the Department. We believe that the financial resources are sufficient to accomplish the Program Educational Objectives and ensure continuity of the two Programs in the Department of Chemical and Environmental Engineering.

In addition to these sources of funding, Program Chairs can request funds from the SEAS Dean for other Program-related needs. If the fund request exceeds the amount in the Dean's budget, the Dean negotiates with the Provost's Office, and where appropriate the Office of the Dean of the Faculty of Arts & Sciences, for additional funds. The Provost also controls a Science Development Fund, which has funds to address unusual opportunities for enhancing the quality of engineering programs. These funds are provided if a compelling argument can be made regarding the benefit to Yale.

The Budget Office is responsible for the development of the Yale University annual operating budgets and long-range financial plans for presentation to and approval by University Officers and the Yale Corporation. The Office of the Provost establishes budget targets for individual units in the Faculty of Arts and Sciences. Unit budgets are established from historical information and projected programmatic needs of the units.

Recurring funding is provided centrally from general appropriations as well as unit specific gift and endowed funds. Budgets are managed by Department Chairs and the SEAS Dean's Office. One-time funding requests for infrastructure improvements and investments in equipment are provided through several independent, merit-based processes, coordinated through the Office of the Provost and the Dean of the School.

Funding levels are sufficient to meet the programmatic needs of the unit. Table 8-1 provides a four-year history of funding levels specific to support of the unit's teaching program.

Table 8-1: Chemical Engineering Teaching Program Funding.

Chemical Engineering	**FY17**	**FY18**	**FY19**	**FY20**
Faculty Salaries (burdened)	2,179,818	2,312,423	2,201,950	2,396,290
Allocated Support Staff Wages (burdened)	322,439	334,309	353,311	310,097
Direct Funded Operating	31,500	31,500	31,500	31,500
Allocated Support for Teaching Programs	25,060	22,414	16,144	11,718
Seminars	15,000	15,000	15,000	15,000
Discretionary	25,000	25,000	25,000	25,000
1x Teaching Equipment Funding	—	123,592	21,854	58,050
Teaching Assistants	328,275	336,825	344,925	353,475
Total	**2,927,092**	**3,201,063**	**3,009,684**	**3,201,131**

Support for Program teaching is the responsibility of several units at Yale: the Department, SEAS, the Graduate School of Arts & Sciences, and the Provost's Office. Examples of teaching support include the funding of graders and teaching assistants, as well as the organization and running of teaching workshops, as detailed below.

Teaching experience is regarded as an integral part of the graduate training program at Yale, and all engineering graduate students are required to serve as a Teaching Fellow for one semester, typically during Year 2. Teaching duties normally involve assisting in laboratories or homework sessions and grading assignments for undergraduate courses; these duties are not expected to require more than 10 hours per week. In order to serve as a Teaching Fellow, graduate students either must be native speakers of English or must have met the oral English proficiency requirement. Graduate students in SEAS are not permitted to teach during their first year of study.

Generally undergraduate courses in engineering are supported with one Teaching Fellow (designated as a "TF10," meaning that the duties will not exceed 10 hours per week) for every 20 students in a lecture course or for every 10 students in a laboratory course. Lecture courses with an enrollment of fewer than 9 students are not awarded a Teaching Fellow. Funds for the Teaching Fellow program are provided by the Yale Graduate School. The assignment of TFs to engineering courses is initially based on the prior year's course enrollment, and then updated after the course shopping period has ended and the course enrollment is finalized. The course instructors work with the DUS and SEAS graduate registrar to identify suitable graduate student TFs for each engineering course. As mentioned above, all Ph.D. students are required to serve as a TF for one semester (TF10), but they are encouraged to be teaching fellows for additional semesters for an increased stipend.

Yale also supports undergraduate teaching via the Poorvu Center for Teaching and Learning. As part of the Office of the Provost, the Poorvu Center works with faculty to enable equitable and engaged teaching. The Center offers programs, funding, consultations, classroom observations, support, and digital resources designed for faculty and lecturers at Yale. One of their larger initiatives is the Faculty Teaching Academy, the goal of which is to engage new Yale faculty (within the first three years of being hired) in structured conversations in communities of practice with peers. Participants in the Faculty Teaching Academy (FTA) must complete six major components (the first of which is intensive training at a Summer Institute on Course Redesign and the last of which is submission of a final program portfolio) during a two-year period. Faculty receive a $3K contribution to their research accounts or professional development accounts upon completion of the program.

In addition, the Poorvu Center runs smaller initiatives for all Yale faculty such as Course (Re)Calibrate, Teaching and Learning Lunches, Diversity and Education events, and the Educational Technology Forum. Their workshops on using digital technology in the classroom (e.g., Poll Everywhere workshops) are popular with faculty seeking to engage students in the classroom via the use of electronic devices. There are also workshops for faculty who wish to learn more about the Canvas@Yale web portal (https://canvas.yale.edu/), Yale's Learning Management System, which includes an integrated set of web-based tools for teaching, learning, and sharing information such as a syllabus creation tool, tools for announcements, threaded discussions, and online file sharing. All students, faculty, and staff at Yale have access to the Canvas@Yale portal.

The Poorvu Center also provides funds to faculty for minor and major course enhancements (Instructional Enhancement Fund and the Rosenkranz Awards for Pedagogical Advancement), for which faculty must apply. The latter awards are relatively large (up to $10K) and the application process is quite competitive.

For Yale faculty as well as faculty at other universities, another Poorvu Center initiative is its set of regional Summer Institutes on Scientific Teaching funded by the Howard Hughes Medical Institute. The Summer Institutes are intensive multi-day workshops held throughout the United States that introduce STEM educators to the principles of evidence-based teaching.

For Yale graduate students, the Poorvu Center provides teaching consultations, classroom observations, and two series of workshops: Fundamentals of Teaching and Advanced Teaching. All first-time Teaching Fellows must complete, at a minimum, the 5-hour workshop entitled Teaching@Yale Day (T@YD), in which they learn about policies and guidelines, gain insight into student and faculty perspectives on graduate teaching, and are introduced to the many teaching resources available at the Poorvu Center. Professional development programming for graduate students is also available, as well as workshops on preparing for the academic job market.

Regarding the process to which resources are provided to maintain and upgrade the infrastructure, facilities and equipment in the program, the Department Chair has access to a large support network to effect change. At one level, the School of Engineering & Applied Science works with the Provost's Office to acquire, maintain and upgrade facilities and equipment. The Greenberg Engineering Teaching Concourse is one example of this process. In this case, the improvements were initiated by the School of Engineering & Applied Science with a request to the Provost. In such cases, once approved, the SEAS works directly with Yale's campus planners and architects to upgrade infrastructure. A similar process is used for renovating classrooms and research labs.

On another level, the Department Chair has access to a support and maintenance network within the School of Engineering & Applied Science. Such support is coordinated through the SEAS Business Office for routine maintenance of infrastructure and for minor renovations. Such work may be accomplished using the School's staff, or with assistance from Yale's Office of Facilities. For equipment maintenance, the Program is assisted by the SEAS Teaching Support Staff.

Regarding the adequacy of resources with respect to the Program and its students, resources have been adequate to attain the Student Outcomes. For example, following the last General Review, when it was determined that the lab facilities were a concern, the School prioritized the need to create new lab space for all programs. As a part of that renewal, Program Faculty requested and were awarded new lab equipment to support a distillation column experiment (Pignat DVI/3000) in the 2017–18 academic year, and a chemical reaction experiment (Pignat RAP/4000) in the 2019–20 academic year. Each serves as one of the six experiments performed by students taking the (ABET-required) CENG 412L course, and also are occasionally used as demonstrations for certain non-lab courses.

C. Staffing

The SEAS faculty-to-student ratio is one of the country's best, providing ample opportunity for students to gain individual access to their professors. Not only has SEAS succeeded in attracting top faculty, it seeks only the best in research, administrative and technical staff — all dedicated to furthering the excellence of the School of Engineering & Applied Science. The Program and School are assisted in these efforts by a fully engaged Yale Office of Human Resources. The University's compensation, benefits, training and development programs help make Yale a desirable and preferred employer.

Administrative support at the School level consists of the Dean, Deputy Dean, Assistant Dean, a business office director, teaching lab specialists, financial managers, a Director of Communications, and several administrative assistants. In addition to the Department Faculty (and the Teaching Assistants), the following individuals within the School of Engineering & Applied Science provide direct support to the Program.

(a) Technical support:
- Teaching lab support specialists (Katherine Schilling, Ph.D., Glenn Weston-Murphy, Kevin Ryan, Nick Bernardo)
- Computer support specialists (Information Technology Services)
- Student computing assistants (Information Technology Services)

(b) Administrative personnel who conduct the business activities supporting our Programs:
- Dean of School of Engineering & Applied Science (Jeffrey Brock)
- Deputy Dean of School of Engineering & Applied Science (Vincent Wilczynski)
- Assistant Dean for Science and Engineering (Sarah Miller)
- Director of Communications (Steven Geringer)
- Director of News and Outreach (William Weir)
- Lead Administrator (Denny Kalenzaga)
- Facilities Operations (Andy Morcus)

(c) Department of Chemical and Environmental Engineering Administrative Support (Ben McManus [Administrative Associate to Program Chair] and Molly McKenna)

D. Faculty Hiring and Retention

New faculty members are hired based on national searches for junior and senior positions. When a person is recommended for a ladder faculty position through the search and voting processes of a department in the Faculty of Arts and Sciences, the recommendation is reviewed by the Dean of Yale College, the Dean of the Graduate School, the Dean of the School of Engineering & Applied Science, or by an appointments committee. Appointments to the rank of assistant professor are reviewed by the Dean of the School of Engineering & Applied Science.

Appointments to the ranks of associate professor on term or with tenure and to full professor are reviewed by the Tenure Appointments and Promotions Committee for the Physical Sciences Division. The policies and procedures for hiring are detailed in the Faculty Handbook that is promulgated by the Provost's Office.

Each new faculty member is provided with a start-up package from the Office of the Provost sufficient to allow them to establish their laboratory and research program. Faculty members are also provided with cost-matching support that can be used to purchase additional major equipment through such programs as the NSF Major Research Instrumentation Program and Defense University Research Instrumentation Program. Funds for travel assistance to national and international scientific meetings for the faculty can also be obtained through the Office of the Provost.

Yale University is very committed to retaining Faculty, and especially so regarding tenured Faculty. In addition to the generous leave policies, Yale has a faculty support and reward system that recognizes success, supports expanding research programs, and strives to meet Faculty professional development and personal growth needs.

E. Support of Faculty Professional Development

The Office of the Provost provides funds for faculty to travel to professional and scientific meetings. For tenured faculty, the maximum amount of reimbursement is $600 per academic year; for non-tenured faculty, the maximum is $1,200 each academic year, and in certain cases persons holding full-time Adjunct appointments are also eligible. To qualify for a travel grant, the faculty member must actively participate in the meeting by delivering a presentation, chairing a panel, serving as an officer of a professional association, contributing as a stated participant in a formal discussion, or participating in a significant way. Speaking as a lecturer or visitor at another university does not qualify for use of these funds, unless the event is a meeting that includes faculty from other universities.

Beginning faculty members are typically provided either a complete or partial release from teaching duties during their first semester at Yale to allow them to develop their research program. The typical teaching load after that period is one course per semester.

Ample sabbatical leaves are provided. Tenured professors are eligible for triennial, one-semester leaves at full salary. As established in Yale's Tenure and Appointments Policy, assistant professors are eligible for a one-year paid leave during Years 2–4 of their initial appointment, and associate professors are eligible for a one-year paid leave in Years 1–2 following their promotion.

PROGRAM CRITERIA

The ABET Program Criteria for Chemical Engineering Programs include one element (Curriculum) containing three parts, each of which will be addressed momentarily. For all required courses mentioned in this chapter, the course artifacts (e.g., the syllabi — which are provided in Appendix A — and supporting material available during the visit) substantiate the attainment of the three-part Curriculum criterion.

Each part of the Curriculum criterion appears in italics below, followed by information about specific courses that address that part of the criterion.

(a) The curriculum must include applications of mathematics, including differential equations and statistics, to engineering problems.

The Program meets this criterion via the mathematics portion of the curriculum, which includes Multivariable Calculus for Engineers (ENAS 151) and Ordinary and Partial Differential Equations with Applications (ENAS 194). Beyond these courses, students apply **differential equations** to engineering problems in CENG 301 (Chemical Kinetics and Chemical Reactors), CENG 315 (Transport Phenomena), CENG 480 (Chemical Engineering Process Control), and MENG 361 (Mechanical Engineering II: Fluid Mechanics). Applications of differential equations also appear in certain electives such as CENG 351 (Biotransport and Kinetics), MENG 441 (Applied Numerical Methods for Differential Equations), and BENG 353 (Introduction to Biomechanics). The application of **statistics** is used in CENG 412L (Chemical Engineering Lab and Design) for error analysis and in some elective courses, such as EENG 406 (Photovoltaic Energy) where statistics are used for analyzing charge carriers.

(b) The curriculum must include college-level chemistry and physics courses, with some at an advanced level, as appropriate to the objectives of the program.

The Program meets this criterion via the science portion of the curriculum, consisting of **general chemistry, organic chemistry including labs, physical chemistry, and calculus-based physics**. In fact, Chemical Engineering students take an equivalent of 10 science course credits. Content at an advanced level is supplied in the two-semester organic chemistry sequence (Organic Chemistry [CHEM 220] and The Organic Chemistry of Life Processes [CHEM 221]), including labs (Laboratory for Organic Chemistry I, II [CHEM 222L, 223L]), and in the two-semester physical chemistry sequence (Physical Chemistry with Applications in the Physical Sciences I, II [CHEM 332, 333]). Note that three of these courses (CHEM 222L, 223L, and 332) are each considered to count equally as "science" and as "engineering topics," as shown in Table 5-1 and as justified in Chapter 5. All of the chemistry and physics courses that the students take prepare them for engineering courses and introduce topics that may be pursued alongside their engineering coursework. Table 5-1 in Chapter 5 lists the course names and numbers.

(c) The curriculum must include the engineering application of these sciences to the design, analysis, and control of processes, including the hazards associated with these processes.

The Program meets this criterion via the **engineering** portion of the curriculum. The required core courses with CENG (and MENG) course numbers are:

- CENG 150: Engineering Improv: An Introduction to Engineering Analysis
- CENG 300: Chemical Engineering Thermodynamics
- CENG 301: Chemical Kinetics and Chemical Reactors
- CENG 315: Transport Phenomena
- MENG 361: Mechanical Engineering II: Fluid Mechanics
- CENG 411: Separation and Purification Processes
- CENG 412L: Chemical Engineering Laboratory and Design
- CENG 416: Chemical Engineering Process Design
- CENG 480: Chemical Engineering Process Control.

Students also take three engineering electives, examples of which were listed in Chapter 1. Additional engineering content comes from ENAS 130 (Introduction to Computing for Engineers and Scientists), which is taught by engineering faculty to a primarily engineering audience; this course is considered to count as half of a "math" course and as half of an "engineering topics" course, as seen in Table 5-1. As explained in item (b) above, half of the course credits of CHEM 222L, 223L, and 332 are counted as engineering content.

Regarding **hazards**, CENG 412L, CENG 416, and CENG 480 each address safety within the Chemical Engineering discipline.

Although Chemical Engineering Laboratory and Design (CENG 412L) has undergone changes, process safety continues to be emphasized in the curriculum. CENG 412L teaches how to identify and mitigate process hazards and promotes the "soft skills" essential to safety: teamwork, problem solving, and communication. Each class meeting opens by integrating process safety into the pre-lab lecture and the hands-on equipment orientation. Faculty encourage students to think critically and apply their lecture knowledge to each experiment, so that students link concepts with the consequences of their actions in lab. As students go through the processes in lab, they keep careful notes of their calculations and actions, which is essential for safety as well as research training. Students gain real-world understanding of how safety systems look and function as they observe and use the safety design features of the apparatuses they use in class. They discuss with faculty the possible routes for equipment failure and damage, including issues unique to pressurized gases and heated liquids and gases. Students learn about the material hazards for the common chemicals and biological agents they encounter in the laboratory, and they create safe handling plans for their experimental sessions with the teaching faculty. CENG 412L prepares students by being an experiential learning environment for building process safety awareness and knowledge while communicating and solving problems in a team. Through practice and experience within the lab, students also gain an understanding and appreciation of the use of PPE and standardized lab safety approaches such as the use of Material Safety Data Sheets.

Students in Chemical Engineering Process Design (CENG 416) learn about process safety both in the instructor's lectures as well as in the capstone design project. In the lectures, students are introduced to process safety by calculating the flammability limits (lower and upper flammability) of flammable gases and liquids. In homework problems and a HYSYS Lab, they apply qualitative and quantitative risk assessment methods such failure modes and effects analysis (FMEA), hazard and operability (HAZOP) analysis, and fault tree analysis (FTA). In the capstone design project, Ethylene production via oxidative dehydrogenation of ethane using oxygen, student teams calculate the flammability limits in air of the reactant, ethane, and the primary product, ethylene. They also compare the flammability limits of ethylene and ethane to those of hydrogen and methane.

Students in Chemical Engineering Process Control (CENG 480) are taught the dynamical implications of instability with an emphasis on the practical hazards of runaway temperatures, pressures, etc. With these considerations in mind, students are taught how to select design parameters to minimize safety risks that would arise from various situations, such as temperature overshoot. In constructing and analyzing linearized models of complex processes, students consider how control systems designed based on the linear models could fail for real non-linear systems, and the resulting cautions that should be taken to ensure stable and safe operation. Students test these concepts by designing controllers based on linear models then use them in realistic non-linear simulations.

Appendix A – Course Syllabi

Required Courses:

- ENAS 130: Introduction to Computing for Engineers and Scientists
- ENAS 194: Ordinary and Partial Differential Equations with Applications
- CENG 150: Engineering Improv: An Introduction to Engineering Analysis
- CENG 300: Chemical Engineering Thermodynamics
- CENG 301: Chemical Kinetics and Chemical Reactors
- CENG 315: Transport Phenomena
- CENG 411: Separation and Purification Processes
- CENG 412L: Chemical Engineering Laboratory and Design
- CENG 416: Chemical Engineering Process Design
- CENG 480: Chemical Engineering Process Control
- CHEM 174: Organic Chemistry for First-Year Students I (can substitute for CHEM 220)
- CHEM 175: Organic Chemistry for First-Year Students II (can substitute for CHEM 221)
- CHEM 220: Organic Chemistry
- CHEM 221: The Organic Chemistry of Life Processes
- CHEM 222L: Laboratory for Organic Chemistry I
- CHEM 223L: Laboratory for Organic Chemistry II
- CHEM 332: Physical Chemistry with Applications in the Physical Sciences I
- CHEM 333: Physical Chemistry with Applications in the Physical Sciences II
- MENG 361: Mechanical Engineering II: Fluid Mechanics

Examples of Electives:

- CENG 351: Biotransport and Kinetics
- CENG 373: Air Pollution Control
- CENG 377: Water Quality Control
- CENG 471: Independent Research
- CENG 473: Air Quality and Energy
- MENG 280: Mechanical Engineering I: Strength and Deformation of Mechanical Elements
- MENG 285: Introduction to Materials Science
- MENG 365: Chemical Propulsion Systems
- MENG 383: Mechanical Engineering III: Dynamics
- MENG 441: Applied Numerical Methods for Differential Equations
- EENG 406: Photovoltaic Energy
- BENG 350: Physiological Systems
- BENG 353: Introduction to Biomechanics
- BENG 434: Biomaterials

Prerequisites:

- CHEM 134L: General Chemistry Laboratory I

- CHEM 136L: General Chemistry Laboratory II
- CHEM 161: General Chemistry I
- CHEM 163: Comprehensive University Chemistry I (can substitute for CHEM 161)
- CHEM 165: General Chemistry II
- CHEM 167: Comprehensive University Chemistry II (can substitute for CHEM 165)
- MATH 112: Calculus of Functions of One Variable I
- MATH 115: Calculus of Functions of One Variable II
- MATH 120: Calculus of Functions of Several Variables (can substitute for ENAS 151)
- ENAS 151: Multivariable Calculus for Engineers
- PHYS 180: University Physics I
- PHYS 181: University Physics II

1. Course number and name: ENAS 130
   Introduction to Computing for Engineers and Scientists

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Beth Anne V. Bennett

4. Textbooks (title, author, publisher, year): None.
   a. Supplemental materials: Lecture slides and sample codes.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An introduction to the use of the C and C++ programming languages and the software packages Mathematica and MATLAB to solve a variety of problems encountered in mathematics, the natural sciences, and engineering. General problem-solving techniques, object-oriented programming, elementary numerical methods, data analysis, and graphical display of computational results.

   b. Prerequisites or co-requisites for the course: MATH 115 or equivalent. Recommended preparation: previous programming experience.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Develop ability to write programs in C and C++ in order to solve mathematical and engineering problems using simple numerical methods, to analyze data, and to visualize data graphically.
      - Develop ability to write programs using a sophisticated software package (MATLAB) in order to solve mathematical and engineering problems using simple numerical methods and using built-in functions for data analysis and graphics.
      - Develop ability to debug computer codes and create properly functioning codes.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Introduction to programming; problem solving using C (data types, I/O, conditionals, operator precedence, loops, functions, scope of a variable, pointers, graphics, arrays, dynamic memory allocation, structures, debugging, recursion); problem solving using MATLAB (arithmetic, variables, matrix operations, scripts, plotting, I/O, debugging, conditionals, loops, functions); problem solving using C++ (function overloading, classes, I/O, more about dynamic array allocation, graphics); applications throughout the course

1. Course number and name: ENAS 194/APHY 194
Ordinary and Partial Differential Equations with Applications

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Mitchell Smooke

4. Textbooks (title, author, publisher, year): Elementary Differential Equations and Boundary Value Problems, 10^{th} edition, by William E. Boyce and Richard C. DiPrima, John Wiley & Sons, Inc., 2012.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Basic theory of ordinary and partial differential equations useful in applications. First- and second-order equations, separation of variables, power series solutions, Fourier series, Laplace transforms.

   b. Prerequisites or co-requisites for the course: ENAS 151 or equivalent, and knowledge of matrix-based operations.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Attain detailed knowledge of analytical techniques for solving differential equations.
      - Develop ability to apply analytical techniques to solve both ordinary differential equations (ODEs) and partial differential equations (PDEs).

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Characterizing differential equations; first-order ODEs; second-order linear ODEs with constant coefficients; mechanical and electrical vibrations; higher-order linear ODEs with constant coefficients; series solutions of second-order linear ODEs with non-constant coefficients; Laplace transforms; systems of first-order linear ODEs; Fourier series; solution of linear PDEs (heat equation, wave equation, and Laplace equation) by separation of variables

1. Course number and name: CENG 150
Engineering Improv: An Introduction to Engineering Analysis

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Michael Loewenberg

4. Textbooks (title, author, publisher, year):
   - Chemical Engineering, An Introduction, by Morton M. Denn, Cambridge, 2012. ISBN 9781107669376.
   - Chemical Engineering Design and Analysis: An Introduction, by T. Michael Duncan & Jeffrey A. Reimer, Cambridge, 1998. ISBN 9780511803352.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
   Mathematical modeling is not a scripted procedure. Models are constrained by physical principles, including conservation laws and experimental observations but this does not provide a closed description. There is a lot more art in mathematical modeling than is commonly acknowledged and improvisation plays a significant role. The artistic aspects are important and intellectually engaging because they often lead to a deeper understanding. This course provides a general introduction to engineering analysis and to chemical engineering principles. Material will include the derivation of governing equations from first principles and the analysis of these equations, including underlying assumptions, degrees of freedom, dimensional analysis, scaling arguments, and approximation techniques. The goal of this course is to obtain the necessary skills for improvising mathematical models for a broad range of problems that arise in engineering, science and everyday life. Students from all majors are encouraged to take this course.

   b. Prerequisite for course: MATH 112.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Apply knowledge of mathematics, science, and engineering.
      - Formulate mathematical models.
      - An ability to design experiments, as well as to analyze and interpret data
      - Familiarity and facility with chemical engineering principles.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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

SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Mass and energy balances; dimensional analysis, dimensionless variables, scaling arguments; introduction to process modeling; introduction to chemical kinetics and chemical reactors; introduction to thermodynamics: first and second laws, thermodynamic engines, refrigerators, thermodynamic cycles; introduction to fluid mechanics and transport phenomena

1. Course number and name: CENG 300
Chemical Engineering Thermodynamics

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: T. Kyle Vanderlick

4. Textbooks (title, author, publisher, year): Introduction to Chemical Engineering Thermodynamics, 7th edition, by J.M. Smith, H.C. Van Ness, M.M. Abbott, and M.T. Swihart, McGraw-Hill, 2018.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Analysis of equilibrium systems. Topics include energy conservation, entropy, heat engines, Legendre transforms, derived thermodynamic potentials and equilibrium criteria, multicomponent systems, chemical reaction and phase equilibria, systematic derivation of thermodynamic entities, criteria for thermodynamic stability, and introduction to statistical thermodynamics.

   b. Prerequisites or co-requisites for the course: MATH 120 or ENAS 151 or permission of instructor.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply the 1st and 2nd Laws of Thermodynamics.
      - Understand and apply thermodynamic principles of vapor-liquid equilibria.
      - Understand and apply thermodynamic principles of chemical reaction equilibria.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Equilibrium; reversibility; ideal gas; 1st and 2nd Laws of Thermodynamics; phase behavior; fugacity; liquid-vapor equilibria; chemical reaction equilibria

1. Course number and name: CENG 301
Chemical Kinetics and Chemical Reactors

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Mingjiang Zhong

4. Textbooks (title, author, publisher, year): Elements of Chemical Reaction Engineering, 5th Edition, H. Scott Fogler, Prentice-Hall

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Physical-chemical principles and mathematical modeling of chemical reactors. Topics include homogeneous and heterogeneous reaction kinetics, catalytic reactions, systems of coupled reactions, selectivity and yield, chemical reactions with coupled mass transport, nonisothermal systems, and reactor design. Applications from problems in environmental, biomedical, and materials engineering.

   b. Prerequisites or co-requisites for course: CENG 300, ENAS 194, or permission of instructor.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply concepts of chemical kinetics
      - Understand and apply concepts of chemical catalysis
      - Understand and apply concepts of mass transport limited chemical kinetics
      - Understand and apply principles of chemical reactors

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Homogeneous and heterogeneous reaction kinetics; catalytic reactions; systems of coupled reactions; selectivity and yield; reactor design; membrane reaction; microelectronic fabrication; biological reactor and enzymatic catalysis; batteries

1. Course number and name: CENG 315/ENVE 315
Transport Phenomena

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: T. Kyle Vanderlick

4. Transport Process and Separation Process Principles, 4th ed., Christie John Geankoplis, Prentice Hall, Upper Saddle River, New Jersey, 2003.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Unified treatment of momentum, energy, and chemical species transport including conservation laws, flux relations, and boundary conditions. Topics include convective and diffusive transport, transport with homogeneous and heterogeneous chemical reactions and/or phase change, and interfacial transport phenomena. Emphasis on problem analysis and mathematical modeling, including problem formulation, scaling arguments, analytical methods, approximation techniques, and numerical solutions.

   b. Prerequisites or co-requisites for course: ENAS 194 or permission of instructor

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Be able to solve problems involving steady and unsteady state heat conduction, convection, and radiation.
      - Be able to solve problems involving mass transfer due to diffusion, chemical reaction, and convection.
      - Be able to size some basic heat and mass transfer equipment.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
      SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Momentum, energy, and chemical species transport including conservation laws, flux relations, and boundary conditions; convective and diffusive transport; transport with homogeneous and heterogeneous chemical reactions and/or phase change; problem formulation, scaling arguments, analytical methods, approximation techniques, and numerical solutions

1. Course number and name: CENG 411
Separation and Purification Processes

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Paul Van Tassel

4. Textbooks (title, author, publisher, year):
J. D.Seader, E. J. Henley, and D. K. Roper, Separation Process Principles, 4th edition

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Theory and design of separation processes for multicomponent and/or multiphase mixtures via equilibrium and rate phenomena. Topics include single-stage and cascaded absorption, adsorption, extraction, distillation, partial condensation, filtration, and crystallization processes. Applications to environmental engineering (air and water pollution control), biomedical-chemical engineering (artificial organs, drug purification), food processing, and semiconductor processing.

   b. Prerequisites or co-requisites for course: CENG 300 or CENG 315 or permission of instructor.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      Theory and design of separation processes for multi-component, multi-phase systems via equilibrium and kinetic phenomena. Topics include single-stage and cascade separations, absorption, distillation, extraction, membrane separations, adsorption, and crystallization. Applications from chemical, environmental, and biomedical engineering are stressed throughout.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Thermodynamics, transport phenomena, single-stage and cascade separations, absorption, distillation, extraction, membrane separations, and adsorption

1. Course number and name: CENG 412L
Chemical Engineering Laboratory and Design

2. Credits and contact hours: 1.0 credits, 4 hours/week

3. Instructor's name: Paul Van Tassel

4. Textbooks (title, author, publisher, year): None.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An introduction to basic experimental methods in chemical engineering, including interpretation, analysis, and modeling of experimental results. Students conduct experiments in chemical reactor kinetics, complex fluids, distillation, heat transfer, and membrane separations.

   b. Prerequisites or co-requisites for course: CENG 300, 301, 315, and 411

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Learn basic chemical engineering experimental methods
      - Design and conduct chemical engineering laboratory experiments
      - Write chemical engineering lab reports

   b. Student outcomes addressed by this course:
      SO 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
      SO 3: An ability to communicate effectively with a range of audiences
      SO 5: An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Chemical reactor kinetics; complex fluids; distillation; heat transfer; membrane separation

1. Course number and name: CENG 416/ENVE 416
   Chemical Engineering Process Design

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Yehia Khalil

4. Textbooks (title, author, publisher, year): Plant Design and Economics for Chemical Engineers, M.S. Peters, K.D. Timmerhaus, and R.E. West, 5th Edition

5. Specific course information:
   a. Brief dscription of the content of the course (catalog description):
      Study of the techniques for and the design of chemical processes and plants, applying the principles of chemical engineering and economics. Emphasis on flowsheet development and equipment selection, cost estimation and economic analysis, design strategy and optimization, safety and hazards analysis, and environmental and ethical considerations.

   b. Prerequisites or co-requisites for course: CENG 300, 301, 315, and 411

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Apply basic science and engineering knowledge toward an understanding of design fundamentals.
      - Apply basic science and engineering knowledge, along with fundamental design knowledge, toward a practical design scenario.
      - Apply physical and biological sciences, engineering, design principles, and sustainability concepts toward a contemporary engineering problem.
      - Develop a sense of professional and ethical responsibility

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 3: An ability to communicate effectively with a range of audiences
      SO 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
      SO 5: An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Chemical engineering design; flowsheet development; process simulation; economic analysis

1. Course number and name: CEng 480
Chemical Engineering Process Control

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Eric Altman

4. Textbooks (title, author, publisher, year):
Process Dynamics and Control, 4th Edition, D.E. Seborg (John Wiley and Sons, 2016)

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Transient regime modeling and simulations of chemical processes. Conventional and state-space methods of analysis and control design. Applications of modern control methods in chemical engineering. Course work includes a design project.

   b. Prerequisites or co-requisites for course: ENAS 194 or permission of instructor.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Apply basic science and engineering knowledge to process dynamics.
      - Learn how to analyze and configure control loops.
      - Learn simulation and modeling methods and data analysis.
      - Design solutions for complex problems.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 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
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
      SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Introduction to control concepts; unsteady-state process modeling; Laplace transforms; transfer functions; control algorithms; closed-loop block diagrams; dynamical response of open-loop systems; dynamical response of closed-loop systems; analysis with MATLAB and simulation with Simulink; general stability criterion; frequency response analysis; selection of control parameters; lags and noise; multiple inputs and multiple outputs; feedforward control; digital control

1. Course number and name: CHEM 174
Organic Chemistry for First-Year Students I

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Tim Newhouse

4. Textbooks (title, author, publisher, year): Organic Chemistry, by Marc Loudon and Jim Parise, 6th ed., Roberts and Company, 2016
   a. Supplemental materials: Study Guide and Solutions Manual, by Jim Parise and Marc Loudon, 6th ed.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An introductory course focused on current theories of structure and mechanism in organic chemistry, their development, and their basis in experimental observation. Attendance at a weekly discussion section required.

   b. Prerequisites or co-requisites for course: Open to first-year students with excellent preparation in chemistry, mathematics, and physics who have taken the department's advanced chemistry placement examination. Normally accompanied by CHEM 222L. Enrollment by placement only.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      Knowledge and understanding of the fundamental principles, methods, structures, and reactions of organic chemistry; an understanding of organic structure; the ability to write reaction mechanisms; the ability to design simple syntheses; the ability to communicate about organic chemistry; and the ability to make reasonable predictions of the behavior of organic compounds or to give reasonable explanation for observed behaviors.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Chemical bonding and chemical structure; alkanes; acids and bases; the curved-arrow notation; alkenes (structure, reactivity, addition reactions); principles of stereochemistry; cyclic compounds and stereochemistry of reactions; noncovalent intermolecular interactions; alkyl halides; alcohols and thiols; ethers, epoxides, glycols, and sulfides; infrared spectroscopy and mass spectrometry

1. Course number and name: CHEM 175
Organic Chemistry for First-Year Students II

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: David A. Spiegel

4. Textbooks (title, author, publisher, year): Organic Chemistry, by Marc Loudon and Jim Parise, 6th ed., Roberts and Company, 2016
   a. Supplemental materials: Study Guide and Solutions Manual, by Jim Parise and Marc Loudon, 6th ed.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Continuation of CHEM 174. Survey of simple and complex reaction mechanisms, spectroscopy, organic synthesis, and the molecules of nature. Attendance at a weekly discussion section required.

   b. Prerequisites or co-requisites for course: CHEM 174. Normally accompanied by CHEM 223L. Enrollment by placement only.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      Knowledge and understanding of the fundamental principles, methods, structures, and reactions of organic chemistry; an understanding of organic structure; the ability to write reaction mechanisms; the ability to design simple syntheses; the ability to communicate about organic chemistry; and the ability to make reasonable predictions of the behavior of organic compounds or to give reasonable explanation for observed behaviors.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered:
   - We start with alkynes (triple bonds) because their properties and patterns of reactivity are reminiscent of those of double bonds, and provide a useful perspective for reviewing past concepts while introducing new ones.
   - We then transition into conjugated systems (i.e., systems wherein pi-bonds are present on adjacent C-atoms) as a basis for expanding the class's understanding of electronic structure and reactivity trends.

- The Diels-Alder reaction is a natural next step; it represents an important reaction of conjugated systems, applies molecular orbital concepts learned in the previous section to C–C bond forming reactions, and introduces HOMO-LUMO theory.
- The Diels-Alder reaction proceeds through a transition state that is uniquely low-energy due to its “aromatic” character. This mechanistic understanding will serve to transition students to learning about properties of stable aromatic systems including benzene and derivatives.
- Carbonyls (C=O bonds) represent a polarized pi-bond with many similar features to C=C bonds studied thus far in the course. In the remainder of the course, students apply their understanding of structure-reactivity trends for C=C bonds to understanding structure-reactivity patterns found among carbonyl-containing compounds. Aldehydes and ketones are perhaps the simplest subclass of carbonyl-containing compounds, and reactivity trends learned for this class of compounds are then extended to carboxylic acids and derivatives, which are somewhat more complex and critically important to biological systems.
- Amines are also integral to living systems, and at the end of the course, students will apply all they’ve learned from previous sections to understanding structure and reactivity of this import compound class.

1. Course number and name: CHEM 220
Organic Chemistry

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Seth Herzon

4. Textbooks (title, author, publisher, year): Organic Chemistry, by Marc Loudon and Jim Parise, 6th ed., Roberts and Company, 2016
   a. Supplemental materials: HGS Molecular Structure Model Kit by W.H. Freeman and Company, or Molecular Visions: The Flexible Molecular Model Kit

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An introductory course covering the fundamental principles of organic chemistry. The laboratory for this course is CHEM 222L.

   b. Prerequisites or co-requisites for course: After college-level general chemistry. Students who have earned a grade lower than C in general chemistry are cautioned that they may not be sufficiently prepared for this course.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      Knowledge and understanding of the fundamental principles, methods, structures, and reactions of organic chemistry; an understanding of organic structure; the ability to write reaction mechanisms; the ability to design simple syntheses; the ability to communicate about organic chemistry; and the ability to make reasonable predictions of the behavior of organic compounds or to give reasonable explanation for observed behaviors.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Chemical bonding and chemical structure; alkanes; acids and bases; the curved-arrow notation; alkenes (structure, reactivity, addition reactions); principles of stereochemistry; cyclic compounds and stereochemistry of reactions; noncovalent intermolecular interactions; alkyl halides; alcohols and thiols; ethers, epoxides, glycols, and sulfides; infrared spectroscopy and mass spectrometry

1. Course number and name: CHEM 221
The Organic Chemistry of Life Processes

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Jason M. Crawford

4. Textbooks (title, author, publisher, year): Organic Chemistry, by Marc Loudon and Jim Parise, 6th ed., Roberts and Company, 2016
   a. Supplemental materials: HGS Molecular Structure Model Kit by W.H. Freeman and Company, or Molecular Visions: The Flexible Molecular Model Kit

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      The principles of organic reactivity and how they form the basis for biological processes. The laboratory for this course is CHEM 223L.

   b. Prerequisites or co-requisites for course: After CHEM 220. Students who have earned a grade lower than C in general chemistry are cautioned that they may not be sufficiently prepared for this course.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      Knowledge and understanding of the fundamental principles, methods, structures, and reactions of organic chemistry; an understanding of organic structure; the ability to write reaction mechanisms; the ability to design simple syntheses; the ability to communicate about organic chemistry; and the ability to make reasonable predictions of the behavior of organic compounds or to give reasonable explanation for observed behaviors.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Nuclear magnetic resonance; alkynes; dienes, resonance, and aromaticity; benzene and its derivatives; allylic and benzene reactivity; aldehydes and ketones; carboxylic acids; carboxylic acid derivatives; enolates, enols, and α,β-unsaturated carbonyl compounds; carbohydrates; thioesters; aromatic heterocycles; amino acids and peptides

1. Course number and name: CHEM 222L
Laboratory for Organic Chemistry I

2. Credits and contact hours: 0.5 credit, 2.5 hours/week

3. Instructor's name: Christine DiMeglio

4. Textbooks (title, author, publisher, year):
Techniques in Organic Chemistry, by Jerry Mohrig, et al., W.H. Freeman and Company, 4th ed., ISBN: 9781464134227

5. Specific course information:
a. Brief description of the content of the course:
First term of an introductory laboratory sequence covering basic synthetic and analytic techniques in organic chemistry. Students are introduced to the concepts and skills required for safe and effective chemical laboratory work by focusing efforts on seven skill areas. Evaluation of student work is an ongoing process, with the aim of continual improvement and ultimate proficiency in all skill areas. Evaluative tools include pre-lab and post-lab assignments, lab notetaking, reports, quizzes, and checkout week exam.

b. Prerequisite: 136L or equivalent, after or concurrently with CHEM 174 or 220.

c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
a. Specific outcomes of instruction:
- Attain proficiency in the following seven skill areas:
  - Safety;
  - Scientific reporting;
  - Chemical information literacy;
  - Spectroscopic analysis;
  - Nonspectroscopic analysis;
  - Standard bench techniques for separation and purification; and
  - Synthesis of organic compounds.

b. Which student outcomes listed in Criterion 3 are addressed by this course:
SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Basic synthetic and analytic techniques in organic chemistry; safety; scientific reporting; chemical information literacy; spectroscopic analysis; nonspectroscopic analysis; standard bench techniques for separation and purification; synthesis of organic compounds

1. Course number and name: CHEM 223L
   Laboratory for Organic Chemistry II

2. Credits and contact hours: 0.5 credit, 2.5 hours/week

3. Instructor's name: Christine DiMeglio

4. Textbooks (title, author, publisher, year):
   Techniques in Organic Chemistry, by Jerry Mohrig, et al., W.H. Freeman and Company, 4th ed., ISBN: 9781464134227

5. Specific course information:
   a. Brief description of the content of the course:
      Second term of an introductory laboratory sequence covering basic synthetic and analytic techniques in organic chemistry.

   b. Prerequisite: 222L or equivalent, after or concurrently with CHEM 174 or 220.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Gain increased proficiency in the following seven skill areas:
        - Safety;
        - Scientific reporting;
        - Chemical information literacy;
        - Spectroscopic analysis;
        - Nonspectroscopic analysis;
        - Standard bench techniques for separation and purification; and
        - Synthesis of organic compounds.

   b. Which student outcomes listed in Criterion 3 are addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered:
   - Practice and refine basic laboratory skills learned in CHEM 222 toward the synthesis, isolation and characterization of organic compounds.
   - Expand the laboratory experience to include one and two-step reaction sequences featuring reaction mechanisms covered in the second term of organic chemistry lecture, such as cycloaddition, FC acylation or alkylation, oxidation, reduction, condensation, esterification.
   - Continue to apply prudent safety practices and expanding their understanding to include risk assessment and mitigation, contributing to an effective laboratory safety culture.

- Learn how to interpret ^{1}H NMR spectra, prepare NMR samples, and collect proton NMR data.
- Use online data bases for chemical safety information, and expand chemical literacy to include chemistry search engines to access and read primary literature.
- Complete the yearlong stepwise education in scientific writing, ending the term by writing a full report.

1. Course number and name: CHEM 332
Physical Chemistry with Applications in the Physical Sciences I

2. Credits and contact hours: 1.0 credits, 3.33 hours/week

3. Instructor's name: Patrick H. Vaccaro

4. Textbooks (title, author, publisher, year): Physical Chemistry, by P. Atkins, J. de Paula, and J. Keeler (Oxford University Press, Oxford UK, 2018) 11th ed., one-volume hard cover edition.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      A comprehensive survey of modern physical and theoretical chemistry, including topic drawn from thermodynamics, chemical equilibrium, electrochemistry, and kinetics.

   b. Prerequisites or co-requisites for course: MATH 120, ENAS 151, or permission of the instructor

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply concepts of thermodynamics.
      - Understand and apply concepts of chemical equilibrium.
      - Understand and apply concepts of electrochemistry.
      - Understand and apply concepts of chemical kinetics.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Properties of gases; thermodynamics (1st, 2nd, and 3rd laws); phase transitions for pure substances; phase transitions for simple mixtures and separation processes; chemical equilibrium; chemical kinetics and reaction dynamics

1. Course number and name: CHEM 333
Physical Chemistry with Applications in the Physical Sciences II

2. Credits and contact hours: 1.0 credits, 3.33 hours/week

3. Instructor's name: Kurt W. Zilm

4. Textbooks (title, author, publisher, year): Physical Chemistry, by P. Atkins, J. de Paula, and J. Keeler (Oxford University Press, Oxford UK, 2018) 11th ed., one-volume hard cover edition.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Continuation of CHEM 332, including topics drawn from quantum mechanics, atomic/molecular structure and spectroscopy, and statistical thermodynamics.

   b. Prerequisites or co-requisites for course: CHEM 328 or 332 or permission of the instructor.
      Recommended preparation: familiarity with differential equations.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply concepts of quantum mechanics.
      - Understand and apply concepts of atomic/molecular structure.
      - Understand and apply concepts of spectroscopy.
      - Understand and apply concepts of statistical thermodynamics.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Quantum theory (introduction, fundamental principles, techniques, and practical applications); atomic structure and atomic spectroscopy; molecular structure and molecular spectroscopy; statistical thermodynamics

1. Course number and name: MENG 361
Mechanical Engineering II: Fluid Mechanics

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Alessandro Gomez

4. Textbooks (title, author, publisher, year): *Fox and McDonald's Introduction to Fluid* Mechanics, 9th edition, by Philip J. Pritchard and John W. Mitchell, John Wiley & Sons, 2015.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Mechanical properties of fluids, kinematics, Navier-Stokes equations, boundary conditions, hydrostatics, Euler's equations, Bernoulli's equation and applications, momentum theorems and control volume analysis, dimensional analysis and similitude, pipe flow, turbulence, concepts from boundary layer theory, elements of potential flow.

   b. Prerequisites or co-requisites for the course: ENAS 194 or equivalent, and physics at least at the level of PHYS 180.

   c. Prerequisite, required, or elective course: Required

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Be able to solve hydrostatics problems to compute pressures and forces.
      - Be able to calculate kinematic properties of flow fields and predict behavior.
      - Be able to apply control-volume analysis to compute average flow properties.
      - Be able to solve the Navier-Stokes equations in simple geometries.
      - Be able to nondimensionalize equations of motion and interpret nondimensional groups.
      - Be able to compute flow rates, pressures, and viscous losses in laminar and turbulent pipe and duct flows.
      - Understand the connection between boundary layers and drag.
      - Be able to predict the behavior of simple one-dimensional compressible flows.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Basic fluid properties, fundamental concepts, and governing equations; elements of hydrostatics; integral (control volume) governing equations; differential governing equations; inviscid incompressible flow; dimensional analysis, scaling, and nondimensionalization of equations; boundary-layer flow and drag; internal viscous flow; introduction to compressible flow; rudiments of turbulence

1. Course number and name: CENG 351/BENG 351/ ENAS 551
Biotransport and Kinetics

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Kathryn Miller-Jensen

4. Textbooks (title, author, publisher, year): None.
   a. Supplemental materials: Readings posted on course website from the following textbooks:
      - An Introduction to Systems Biology: Design Principles of Biological Circuits, by Uri Alon, Chapman & Hall/CRC Press, 2007;
      - Receptors: Models for Binding, Trafficking, and Signaling, by Douglas A. Lauffenburger and Jennifer J. Linderman, Oxford University Press, 1993;
      - Drug Delivery: Engineering Principles for Drug Therapy, by W. Mark Saltzman, Oxford
        University Press, 2001;
      - Transport Phenomena in Biological Systems, 2nd edition, by George A. Truskey, Fan Yuan, and David F. Katz, Prentice Hall, 2009; and
      - Biochemistry, 4th edition, by Donald Voet and Judith G. Voet, John Wiley & Sons, 2011.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Creation and critical analysis of models of biological transport and reaction processes. Topics include mass and heat transport, biochemical interactions and reactions, and thermodynamics. Examples from diverse applications, including drug delivery, biomedical imaging, and tissue engineering.

   b. Prerequisites or co-requisites for the course: MATH 115, ENAS 194; BIOL 101 and 102; CHEM 161, 163, or 167; BENG 249.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Learn and understand fundamental principles to quantitatively and critically analyze biomolecular interactions in biological settings.
      - Be able to apply these fundamental principles to solve problems in biology and medicine, including analysis of cellular signaling networks, rational drug design, and strategies for drug delivery.
      - Be able to connect principles covered in this course to other biomedical engineering courses and research tracks.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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

7. Brief list of topics to be covered: Protein-ligand binding; thermodynamics of biochemical reactions; isothermal titration calorimetry; binding kinetics; multivalent binding and cooperativity; enzymes (Michaelis-Menten kinetics, regulation, inhibition); time-scale analysis of quasi-steady-state approximation; sensitivity analysis; modeling gene expression; receptor-mediated endocytosis and trafficking; generalized conservation equations for biotransport; diffusion, convection, homogeneous and heterogeneous reactions; transient and steady-state; oxygen transfer and delivery; diffusion in microfluidic biosensors

1. Course number and name: CENG 373/ENVE 373/F&ES 773
Air Pollution Control

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Drew Gentner

4. Textbooks (title, author, publisher, year): Atmospheric Chemistry and Physics, by J.H. Seinfeld and S.N. Pandis (Wiley, 2016) and Introduction to Atmospheric Chemistry, by D. J. Jacob (Princeton University Press, 1999).
   a. Supplemental materials: Air Pollution Control Engineering, by N. de Nevers (Waveland Press, 2010) – optional.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An overview of air quality problems worldwide with a focus on emissions, chemistry, transport, and other processes that govern dynamic behavior in the atmosphere. Quantitative assessment of the determining factors of air pollution (e.g., transportation and other combustion–related sources, chemical transformations), climate change, photochemical "smog," pollutant measurement techniques, and air quality management strategies.

   b. Prerequisites or co-requisites for the course: ENVE 120 (or permission of instructor).

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
   - Be able to identify, understand, and analyze air quality problems through knowledge of the different types of air pollution, their sources, chemistry, historical trends, and regulations.
   - Be able to apply methods/knowledge learned in the class to assess and model the behavior and fate of pollutants in the atmosphere, identify the determining factors of air pollution, and evaluate the effectiveness of air pollution control strategies in varying locations.
   - Understand and be able to determine the characteristics of pollutants that influence impacts in the atmosphere, and apply this knowledge to evaluate emerging pollutants and potential environmental impacts.
   - Apply engineering science skills used in classroom activities (e.g. analytical methods, presentation skills with data/results) to individual exercises and the research project.
   - Understand the historical evolution, context, and legislation of air pollution policy.
   - Be able to develop simple models that quantify the transport and chemistry of air pollution.
   - Analyze air quality standards, regional differences in air quality concerns, and be able to apply techniques for measuring and categorizing air quality.

b. Student outcomes addressed by this course:
   - SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
   - SO 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
   - SO 3: An ability to communicate effectively with a range of audiences
   - SO 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
   - SO 5: An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
   - SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
   - SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Human health effects and environmental impacts of air pollution; scales of air pollution problems: local to global; fundamental characteristics of particles and gases: physical/chemical parameters, chemical composition, and size distributions; atmospheric chemistry of gases and particles, ozone chemistry, gas-to-particle conversion; sources of air pollution (biogenic and anthropogenic emissions and their interactions); energy choices, emissions, and air quality; combustion fuels and emissions; atmospheric transport phenomena, modeling and the importance of meteorology; pollution mitigation strategies and regional differences in emissions, chemistry, and meteorology; air pollution control technologies: power plants, motor vehicles, and industry; climate change and air quality (radiative forcings of air pollutants, co-benefits, carbon intensity); methods and instrumentation for the measurement of air pollution, and approaches to analyzing air quality; engineering science skills (use of statistics, publishing and peer review, experimental research methods)

1. Course number and name: CENG 377/ENVE 377
   Water Quality Control

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Jaehong Kim

4. Textbooks (title, author, publisher, year): Theory and Practice of Water and Wastewater Treatment, by Ronald. L. Droste, John Wiley & Sons, Inc., 1997

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Study of the preparation of water for domestic and other uses and treatment of waste water for recycling or discharge to the environment. Topics include processes for removal of organics and inorganics, regulation of dissolved oxygen, and techniques such as ion exchange, electrodialysis, reverse osmosis, activated carbon absorption, and biological methods.

   b. Prerequisites or co-requisites for the course: ENVE 120 (or permission of instructor).

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
   - Learn and understand fundamentals of water and wastewater treatment unit operations including coagulation, sedimentation, disinfection, filtration, oxidation, membrane separation, and biological process.
   - Understand how to approach water and wastewater treatment unit operators from the perspective of engineering fundamentals.
   - Be able to use chemical principles and transfer process principles as well as mathematics to perform mass balances and design reactors and systems for the water quality control.
   - Develop analytical thinking skills and engineering problem solving skills that are necessary to tackle ever-increasing water quality problems.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 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
      SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Water and wastewater treatment operations; mass balance and hydraulic flow regimes; disinfection; mass transfer and aeration; analysis and constituents in water; coagulation and flocculation; screening and sedimentation; filtration and membrane processes; aerobic biological treatment; state-of-art water treatment technologies; field trip to Whitney Water Treatment Plant in Hamden, CT

1. Course number and name: CENG 471
   Independent Research

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Michael Loewenberg

4. Textbooks (title, author, publisher, year): None.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Faculty-supervised individual student research and design projects. Emphasis on the integration of mathematics with basic and engineering sciences in the solution of a theoretical, experimental, and/or design problem.

   b. Prerequisites or co-requisites for the course: Permission of adviser and director of undergraduate studies.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Develop the ability to design and outline a plan for solving an engineering problem.
      - Apply knowledge gained in earlier engineering courses to solve an engineering problem (i.e., complete a research or design project) under the supervision of a SEAS adviser.
      - Gain practice in technical communication skills by preparing a written report or delivering a final presentation to an audience composed of engineering faculty and fellow undergraduates.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 3: An ability to communicate effectively with a range of audiences
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
      SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Projects completed by Chemical Engineering students in the Class of 2020 were as follows:

   - Binding and optimization of molecular iridium-based catalysts on BiVQ4 semiconductor material surfaces for photoelectrocatalytic oxygen evolution employing a layered semiconducting architecture
     Student: Chris Karpikov
     Adviser: Prof. Gary Brudvig, Chemistry
     Semester: Spring 2019

- Safely intercalating ions into multi-walled carbon nanotubes (MWCNTs) to stabilize superconductive compounds
  Student: Anthony Ratinov
  Adviser: Prof. Lisa Pfefferle, Chemical and Environmental Engineering
  Semester: Fall 2018

- Synthesizing and characterizing copper-oxide sheets
  Student: Jimmy Rogers
  Adviser: Prof. Lisa Pfefferle, Chemical and Environmental Engineering
  Semester: Spring 2019

- Developing and refining a process for the scalable synthesis of triblock brush copolymers consisting of PDMS, PEO, and PtBA blocks
  Student: George Zhang
  Adviser: Prof. Mingjiang Zhong, Chemical and Environmental Engineering
  Semester: Fall 2018

- Synthesis of ternary brush block copolymers for orientation controlled thin-film self-assembly
  Student: George Zhang
  Adviser: Prof. Mingjiang Zhong, Chemical and Environmental Engineering
  Semester: Spring 2019

1. Course number and name: CEN 473/ENVE 473/F&ES 777
Air Quality and Energy

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Drew Gentner

4. Textbooks (title, author, publisher, year): Atmospheric Chemistry and Physics, by J.H. Seinfeld and S.N. Pandis (Wiley, 2016).
   a. Supplemental materials: Journal articles and other materials posted on the course website

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      The production and use of energy explored as a source of air pollution worldwide. Assessment of emissions and physical/chemical processes; the effects of emissions from energy sources; the behavior of pollutants in energy systems and in the atmosphere. Topics include traditional and emerging energy technology, climate change, atmospheric aerosols, tropospheric ozone, and transport/modeling/mitigation.

   b. Prerequisites or co-requisites for the course: CENG 373

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Learn and understand the impacts and behavior of emissions from energy sources in order to effectively address the impacts and regulation of air quality.
      - Be able to assess emissions and physical/chemical processes in order to determine how pollutants from energy systems behave in the atmosphere.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 3: An ability to communicate effectively with a range of audiences
      SO 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
      SO 5: An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered:

- Particle and gas basics: sources, physical/chemical parameters and behavior
- Physical dynamics of pollutants in the atmosphere: transport, fate, and impacts on humans, climate, and the environment
  - Particle and reactive gas deposition
  - Gas–particle interactions/kinetics; particle–particle interactions
  - Particle kinetics and electrostatics
  - Atmospheric transport modeling (theory and models)
- Atmospheric chemistry of gases and particles
  - Chemical reaction mechanisms of prevalent chemical compound classes with day- and night-time chemistry
  - Formation of ozone and secondary organic aerosol
  - Multiphase and aqueous chemistry
  - The role of aerosol phase state
- Emissions of gases and particles from energy production and use
  - Combustion chemistry
  - Effects of fuel types on air quality and climate
  - Climate change and air quality: co-benefits
  - Emissions from motor vehicles and other transportation fuel use
  - Power generation for electricity and industry
  - Mitigation strategies in urban areas
  - Source apportionment methods (e.g. chemical mass balance, positive matrix factorization)
  - Energy abroad: Energy choices and developing regions; human health and environmental impacts
  - Approaching energy production/use from the life cycle analysis (LCA) framework
    - Emissions from extraction, processing, storage/transport, and combustion
    - Air quality with emerging energy technologies (e.g. hydraulic fracturing, oil sands, biofuels)
- Methods/techniques/instrumentation for the sampling, measurement, and control of air pollution (covered throughout the course)

1. Course number and name: MENG 280
Mechanical Engineering I: Strength and Deformation of Mechanical Elements

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Eric Brown

4. Textbooks (title, author, publisher, year): Statics and Mechanics of Materials, 4th edition, by Russell C. Hibbeler, Pearson, 2014.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Elements of statics; mechanical behavior of materials; equilibrium equations, strains and displacements, and stress-strain relations. Elementary applications to trusses, bending of beams, pressure vessels, and torsion of bars.

   b. Prerequisites or co-requisites for the course: PHYS 180 or 200, and MATH 115.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Be able to analyze a rigid structure to determine if it is in mechanical equilibrium, and determine forces and torques on different components, including complex networks (trusses) with many parts.
      - Be able to calculate stress and strain in materials based on applied forces and torques.
      - Be able to describe and analyze deformation and failure of materials in terms of stress and strain.
      - Be able to analyze materials subject to different types of loads, such as tension/compression of columns, bending of beams, torsion of shafts, and shear, and materials subject to combinations of these loads (e.g., pressure vessels).
      - Be able to design optimal part sizes to avoid any type of failure while minimizing weight or cost.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Rigid body equilibrium, trusses, external/internal forces, stress, strain, principal stress, stiffness, toughness, strength, plasticity, deformation under axial loads, thermal stress, internal moments, deflection of beams under various loads, bending energy, buckling, material failure

1. Course number and name: MENG 285
Introduction to Materials Science

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Sudhangshu Bose

4. Textbooks (title, author, publisher, year): Materials Science and Engineering: An Introduction, 8th edition, by William D. Callister, Jr., and David G. Rethwisch, John Wiley & Sons, 2010 (same text as for MENG 286L).

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Study of the atomic and microscopic origin of the properties of engineering materials: metals, glasses, polymers, ceramics, and composites. Phase diagrams; diffusion; rates of reaction; mechanisms of deformation, fracture, and strengthening; thermal and electrical conduction.

   b. Prerequisites or co-requisites for the course: Elementary calculus and background in basic mechanics (deformation, Hooke's law) and structure of atoms (orbitals, periodic table).

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Provide an introduction to the principles, design, and application of a wide range of engineering materials (metals, semiconductors, polymers, ceramics, and composites).
      - Develop an understanding of the relationships among processing, microstructure, and properties in materials science.
      - Prepare students to be able to evaluate and compare structural theories with experimental results obtained in the laboratory when they take MENG 286L.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Atomic and microscopic origin of the properties of engineering materials such as metals, ceramics, glasses, polymers, semiconductors, and composites; phase diagrams, diffusion, heat treatment, and rates of reaction; mechanisms of deformation and fracture under steady state, cyclic, and thermal loads, and their implications in practical applications; mechanisms to strengthening materials; design and application of materials; processing of classical (glass, steel) as well as modern (optical fibers, nano materials) materials; basics of materials and component failure in real applications and associated mechanisms.

1. Course number and name: MENG 365
Chemical Propulsion Systems

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Ronald Lehrach

4. Textbooks (title, author, publisher, year): Mechanics and Thermodynamics of Propulsion, 2nd edition, by Philip Hill and Carl Peterson, Pearson, 1992.
   a. Supplemental materials: In-class notes and additional reference materials provided online.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Study of chemical propulsion systems. Topics include review of propulsion fundamentals; concepts of compressible fluid flow; development and application of relations for Fanno and Rayleigh flows; normal and oblique shock systems to various propulsion system components; engine performance characteristics; fundamentals of turbomachinery; liquid and solid rocket system components and performance.

   b. Prerequisites or co-requisites for the course: MENG 361 or permission of instructor.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand the place of various propulsion systems in the flight envelope from low to hypersonic speeds.
      - Be able, from an aero/thermodynamic and compressible fluid flow standpoint, to characterize the performance of system components and integrated system performance.
      - Understand the principles of turbomachinery and liquid- and solid-fueled rocketry, including staging.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
      SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Overview of chemical propulsion systems; propulsion fundamentals (conservation laws and the laws of thermodynamics); compressible fluid flow; system components; system performance; liquid- and solid-fueled rockets (including staging)

1. Course number and name: MENG 383
   Mechanical Engineering III: Dynamics

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Alex Tsai

4. Textbooks (title, author, publisher, year): Engineering Mechanics: Dynamics, 5th edition, by Anthony Bedford and Wallace Fowler, Prentice-Hall, 2007.
   a. Supplemental materials: Engineering Mechanics: Dynamics, 14th edition, Russell Hibbeler, Pearson Higher Education, Inc., 2016.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      The derivation, analysis, and implementation of numerical methods for the solution of Kinematics and dynamics of particles and systems of particles. Relative motion; systems with constraints. Rigid body mechanics; gyroscopes.

   b. Prerequisites or co-requisites for the course: PHYS 180 or 200, and MATH 120 or ENAS 151.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and derive equations of motion for particles and rigid bodies.
      - Express equations of motion in various coordinate systems.
      - Apply conservation of energy, impulse and momentum equations to solve for positions, velocities, and accelerations of moving objects for rectilinear and curvilinear motion.
      - Derive and apply equations of motion for systems having rotating and translating axes
      - Be able to solve problems involving relative general plane motion.
      - Predict the motion of systems under free and forced vibrations with and without viscous damping.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 3: An ability to communicate effectively with a range of audiences
      SO 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

7. Brief list of topics to be covered: Particle kinetics and kinematics, including: curvilinear motion in Cartesian, normal and tangential, and cylindrical components, relative motion, energy methods, linear and angular momentum, variable mass systems, general rigid-body motion including rotation and translation, moving reference frames, impacts, gyroscopic motion, and the study of systems undergoing viscous and damped vibrations

1. Course number and name: MENG 441/ENAS 441/ENAS 748
   Applied Numerical Methods for Differential Equations

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Beth Anne V. Bennett

4. Textbooks (title, author, publisher, year): None.
   a. Supplemental materials: Handouts written by the instructor.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      The derivation, analysis, and implementation of numerical methods for the solution of ordinary and partial differential equations, both linear and nonlinear. Additional topics such as computational cost, error estimation, and stability analysis are studied in several contexts throughout the course.

   b. Prerequisites or co-requisites for the course: MATH 115, and MATH 222 or MATH 225, or equivalents; ENAS 130 or some knowledge of Matlab, C++, or Fortran programming; ENAS 194 or equivalent. ENAS 440 is not a prerequisite.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Develop ability to derive numerical methods and apply them to engineering-related mathematical problems in a way that minimizes computational cost.
      - Develop ability to choose which numerical method to use for a particular problem, based on issues of method efficiency, storage requirements, and likelihood of convergence.
      - Develop ability to question numerical results, to estimate the level of accuracy of the results, and to convey conclusions in written paragraphs with well-supported arguments.
      - Develop ability to solve engineering-related mathematical problems that have no analytical solution (or whose analytical solution is prohibitively complicated to derive), after recasting problems in an appropriate form that involves ordinary differential equations (ODEs) or partial differential equations (PDEs).

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Numerical solution of ODE initial value problems; numerical solution of ODE boundary value problems; numerical solution of parabolic PDEs; numerical solution of hyperbolic PDEs; numerical solution of elliptic PDEs; computational cost, error estimation, and stability analysis (covered for most numerical solution methods)

1. Course number and name: EENG 406/ENAS 806
   Photovoltaic Energy

2. Credits and contact hours: 1.0 credits, 2.5 hours/week + 2 lab sessions throughout the term

3. Instructor's name: Fengnian Xia

4. Textbooks (title, author, publisher, year): The Physics of Solar Cells, by Jenny Nelson, Imperial College Press, 2003 (optional text).
   a. Supplemental materials: Materials posted to the course website.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Survey of photovoltaic energy devices, systems, and applications, including review of optical and electrical properties of semiconductors. Topics include solar radiation, solar cell design, performance analysis, solar cell materials, device processing, photovoltaic systems, and economic analysis.

   b. Prerequisites or co-requisites for the course: EENG 320 or permission of instructor.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Gain the necessary background and analytical skills to understand established and emerging photovoltaic technologies.
      - Gain familiarity with a diverse range of photovoltaic materials.
      - Connect material properties to aspects of solar cell design, processing, and performance.
      - Be able to complete a final project and presentation that explore both the applications and limitations of photovoltaic technology.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 3: An ability to communicate effectively with a range of audiences
      SO 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
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Device physics of photovoltaics; statistics of charge carriers in and out of equilibrium; design of solar cells; optical, electrical, and structural properties of semiconductors relevant to photovoltaics

1. Course number and name: BENG 350/MCDB 310/MCDB 550/ENAS 550
Physiological Systems

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: W. Mark Saltzman and Stuart Campbell

4. Textbooks (title, author, publisher, year): Medical Physiology, 3rd edition, by Walter Boron and Emile Boulpaep, Elsevier, 2016.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Regulation and control in biological systems, emphasizing human physiology and principles of feedback. Biomechanical properties of tissues emphasizing the structural basis of physiological control. Conversion of chemical energy into work in light of metabolic control and temperature regulation.

   b. Prerequisites or co-requisites for the course: CHEM 165 or 167 (or CHEM 113 or 115), or PHYS 180 and 181; MCDB120, or BIOL 101 and 102.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Develop a foundation in human physiology by understanding the homeostasis of vital parameters within the body, and the biophysical properties of cells, tissues, and organs.
      - Apply knowledge of chemistry, physics, and biology to human physiology.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Cell and membrane physiology; physical basis of blood flow; mechanisms of vascular exchange, cardiac performance, and regulation of overall circulatory system; respiratory physiology (mechanics of ventilation, gas diffusion, and acid-base balance); renal physiology (formation and composition of urine and the regulation of electrolyte, fluid, and acid-base balance); digestive system (absorption of nutrients and fluid and electrolyte balance); hormonal regulation (applied to metabolic control and to calcium, water, and electrolyte balance); nerve cells (synaptic transmission and simple neuronal circuits within the central nervous system); special senses (considered in the framework of sensory transduction)

1. Course number and name: BENG 353/PHYS 353/ENAS 558
   Introduction to Biomechanics

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Michael P. Murrell

4. Textbooks (title, author, publisher, year): None.
   a. Supplemental materials: Readings posted on course website from the following textbooks:
      - An Introduction to Biomechanics: Solids and Fluids, Analysis and Design, by Jay D. Humphrey and Sherry L. O'Rourke, Springer, 2015.
      - Foundations for Biomechanics and Biotransport: A First Course for Biomedical Engineers, by Jay D. Humphrey (PDF handouts).
      - Mechanics of Motor Proteins and the Cytoskeleton, by Jonathon Howard, Sinauer Associates, 2001.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An introduction to the biomechanics used in biosolid mechanics, biofluid mechanics, biothermomechanics, and biochemomechanics. Diverse aspects of biomedical engineering, from basic mechanobiology to the design of novel biomaterials, medical devices, and surgical interventions.

   b. Prerequisites or co-requisites for the course: PHYS 180, 181, MATH 115, and ENAS 194.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand Navier-Stokes equations and conservation laws in fluid mechanics.
      - Be able to use continuum mechanics to understand cell response to stress in culture.
      - Be able to determine constitutive laws from thermodynamic potentials.
      - Understand how viscometers measure viscosity of viscoelastic materials.
      - Understand first and second laws of thermodynamics.
      - Understand relationships between biomechanics and other areas of biomedical engineering.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Intermolecular forces; kinematics; elasticity; fluid mechanics; viscoelasticity; poroelasticity; basic thermodynamics; macromolecular mechanics; membrane mechanics; models of cell mechanics; cell behaviors; experimental methods; special topics

1. Course number and name: BENG 434/ENAS 534
Biomaterials

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Anjelica Gonzalez

4. Textbooks (title, author, publisher, year): Biomaterials Science: An Introduction to Materials in Medicine, 3rd edition, by Buddy D. Ratner, Allan S. Hoffman, Frederick J. Schoen, and Jack E. Lemons, Academic Press, 2013, and Introduction to Materials Science for Engineers, 8th edition, by James F. Shackelford, Prentice Hall, 2015.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Introduction to the major classes of biomedical materials: ceramics, metals, and polymers. Their structure, properties, and fabrication connected to biological applications, from implants to tissue-engineered devices and drug-delivery systems.

   b. Prerequisites or co-requisites for the course: CHEM 165 (or CHEM 113 or 115); organic chemistry recommended.

   c. Prerequisite, required, or elective course: Elective

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand corrosion and degradation of materials.
      - Calculate stress and strain on bones and tissues during human activity.
      - Determine the elastic moduli of fiber-based materials.
      - Design a hip implant prosthesis, coronary artery, and replacement body tissues.
      - Understand causes of tissue inflammation.
      - Identify key features of stress versus strain relation for brittle materials.
      - Understand nucleation and growth of crystals nuclei in metals.
      - Understand merits of different cryopreservation methods.
      - Design drug delivery systems.
      - Understand the patent process.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 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
      SO 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

SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Atomic bonds and crystalline structures; bulk properties; surface properties; mechanical properties of materials; polymeric materials and applications; biomaterials for drug delivery; cellular interactions with biomaterials; bioceramics, bioglass, biocomposites, and applications; metals, composites, and applications; mimicry of natural materials; applications of natural materials

1. Course number and name: CHEM 134L
General Chemistry Laboratory I

2. Credits and contact hours: 0.5 credit, 3 hours/week

3. Instructor's name: Narasimhan Ganapathi

4. Textbooks (title, author, publisher, year): None.
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5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An introduction to basic chemistry laboratory methods. Techniques required for quantitative analysis of thermodynamic processes and the properties of gases.

   b. Prerequisites or co-requisites for the course: To accompany or follow CHEM 161 or 163. May not be taken after a higher-numbered laboratory course.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply basic chemistry lab principles.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Chemical equilibrium; chemical kinetics; stoichiometry

1. Course number and name: CHEM 136L
General Chemistry Laboratory II

2. Credits and contact hours: 0.5 credit, 3 hours/week

3. Instructor's name: Narasimhan Ganapathi

4. Textbooks (title, author, publisher, year): None.
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5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Introduction to rate and equilibrium measurements, acid-base chemistry, synthesis of organic compounds, and qualitative/quantitative analysis.

   b. Prerequisites or co-requisites for the course: After CHEM 134L or the equivalent in advanced placement. To accompany or follow CHEM 165 or 167. May not be taken after a higher-numbered laboratory course.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply basic chemistry lab principles.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Chemical equilibrium; acid-base chemistry; synthesis of organic compounds; qualitative/quantitative analysis

1. Course number and name: CHEM 161
General Chemistry I

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Paul Cooper

4. Textbooks (title, author, publisher, year): Chemistry: The Science in Context, by Thomas R. Gilbert, Rein V. Kirss, Natalie Foster, Stacey Lowery Bretz, and Geoffrey Davies, 5th ed.
   a. Supplemental materials: Practice problems and problem sets are done using Sapling Learning. Students must register for Sapling Learning online.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      A comprehensive survey of modern descriptive, inorganic, and physical chemistry. Atomic theory, stoichiometry, thermochemistry, chemical periodicity, concepts in chemical bonding, and the shapes of molecules. Appropriate either as a first chemistry course or for students with one year of high school chemistry.
   b. Prerequisites or co-requisites for the course: Enrollment by placement only. Normally accompanied by CHEM 134L.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply basic principles of aqueous chemistry and thermochemistry.
      - Understand and apply basic properties of gases.
      - Understand and apply basic principles of chemical bonding, molecular geometry, and intermolecular forces.
      - Understand how atomic and molecular properties affect macroscopic properties of solutions and solids.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Particles of matter; atoms, ions, and molecules; stoichiometry; aqueous chemistry; thermochemistry; properties of gases; quantum model of atoms (waves, particles, and periodic properties); chemical bonds; molecular geometry; intermolecular forces; solutions (properties and behavior); solids (crystals, alloys, and polymers)

1. Course number and name: CHEM 163
Comprehensive University Chemistry I

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: James Mayer

4. Textbooks (title, author, publisher, year): Principles of Modern Chemistry, 8th edition, by David W. Oxtoby, H. Pat Gillis, and Laurie J. Butler, Cengage Learning, 2015.
   a. Supplemental materials: Practice problems and problem sets are done using Sapling Learning. Students must register for Sapling Learning online.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
   An in-depth examination of the principles of atomic, molecular, and stolid state chemistry, including structures, periodicity, and chemical reactivity. Topics include the quantum mechanics of atoms and chemical bonding, and inorganic, organic, and solid-state molecules and materials. For students with strong secondary school exposure to general chemistry.

   b. Prerequisites or co-requisites for the course: Enrollment by placement only.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand course topics, which range from the quantum mechanics of atoms and chemical bonding, to inorganic, organic, and solid-state molecules and materials.
      - Develop skills in scientific analysis and inquiry.

   b. Student outcomes addressed by this course:
   SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
   SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Review of basic chemistry; electronic structure: quantum mechanics, atomic structure, and molecular structure; bonding and reactivity through the lens of organic chemistry; polymers; transition metal complexes and solids

1. Course number and name: CHEM 165
General Chemistry II

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Paul Cooper

4. Textbooks (title, author, publisher, year): Chemistry: The Science in Context, by Thomas R. Gilbert, Rein V. Kirss, Natalie Foster, Stacey Lowery Bretz, and Geoffrey Davies, 5th ed.
   a. Supplemental materials: Practice problems and problem sets are done using Sapling Learning. Students must register for Sapling Learning online.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Topics include kinetics, chemical equilibrium, acid-base chemistry, free energy and entropy, electrochemistry, and nuclear chemistry.

   b. Prerequisites or co-requisites for the course: CHEM 161. Normally accompanied by CHEM 136L.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply basic chemical equilibria principles.
      - Understand and apply basic chemical kinetics principles.
      - Understand and apply basic principles of main group, nuclear, coordination, and organic chemistry.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Chemical kinetics; chemical equilibria; acids and bases; acid-base equilibria; aqueous equilibria; thermodynamics (spontaneous and nonspontaneous reactions and processes); electrochemistry; nuclear chemistry; organic and biological molecules; main group chemistry; transition elements (biological and medical applications)

1. Course number and name: CHEM 167
Comprehensive University Chemistry II

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Kurt Zilm

4. Textbooks (title, author, publisher, year): Principles of Modern Chemistry, 8th edition, by David W. Oxtoby, H. Pat Gillis, and Laurie J. Butler, Cengage Learning, 2015.
   a. Supplemental materials: Practice problems and problem sets are done using Sapling Learning. Students must register for Sapling Learning online.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Topics include kinetics, chemical equilibrium, acid-base chemistry, free energy and entropy, electrochemistry, and nuclear chemistry.

   b. Prerequisites or co-requisites for the course: CHEM 163, or with equivalent placement. Normally accompanied by CHEM 136L.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand and apply basic chemical equilibria principles.
      - Understand and apply basic chemical kinetics principles.
      - Understand and apply basic principles of main group, nuclear, coordination, and organic chemistry.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
      SO 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

7. Brief list of topics to be covered: Kinetic theory, gases, intermolecular potentials; solids, liquids, surface tension; solutions, mixtures, colligative properties; thermodynamics and thermochemistry; entropy and spontaneous processes; free energy and chemical equilibria; acid-base equilibria; solubility and precipitation reactions; electrochemistry; chemical kinetics; nuclear chemistry; spectroscopy

1. Course number and name: MATH 112
Calculus of Functions of One Variable I

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Thomas Hille

4. Textbooks (title, author, publisher, year): Calculus: Early Transcendentals, 8th edition, by James Stewart, Cengage Learning, 2016 (Chapters 2–5 and 9).
   a. Supplemental materials: Homework modules on the course website.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Limits and their properties. Definitions and some techniques of differentiation and the evaluation of definite integrals, with applications. Use of the software package Mathematics to illustrate concepts.

   b. Prerequisites or co-requisites for the course: No prior acquaintance with calculus or computing assumed. May not be taken after MATH 110 or 111.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Gain an understanding of the concepts that underlie the subject in three ways: abstractly (using the language of limits), geometrically, and via some physical interpretations.
      - Be able to apply the concepts in problem solving.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Review of functions and their combinations and graphs, review of trigonometry; exponential function, inverse functions, logarithms; limits and continuity, intermediate value theorem; limits and infinity, asymptotes, tangents, and velocities, derivatives; derivatives of polynomials and exponentials, the product and quotient rules; derivatives of trigonometric functions, the Chain Rule; related rates, linear approximation; maximum and minimum values, the Mean Value Theorem, the derivative and the graph; L'Hopital's Rule, curve sketching; max-min problems, Newton's Method

1. Course number and name: MATH 115
   Calculus of Functions of One Variable II

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Aaron Calderon

4. Textbooks (title, author, publisher, year): Calculus: Early Transcendentals, 8th edition, by James Stewart, Cengage Learning, 2016.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      A continuation of MATH 112. Applications of integration, with some formal techniques and numerical methods. Improper integrals, approximation of functions by polynomials, infinite series. Exercises involve the software package Mathematica.

   b. Prerequisites or co-requisites for the course: After MATH 112 or equivalent; open to freshmen with some preparation in calculus. May not be taken after MATH 116.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand how to take complex problems and break them up into simpler ones.
      - Be able to apply concepts of Riemann sums, integration, Taylor series, and parametric and polar equations to solve problems in geometry, economics, biology, and physics.
      - Appreciate the beautiful way that the course topics fit together within the theory of calculus, the mathematics of change.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Antiderivatives; methods to approximate definite integrals and to analyze the error in those approximations; sequences; infinite series; representation of functions with Taylor series; computation of lengths, areas, and volumes of geometric objects; modeling curves using parametric and polar equations

1. Course number and name: MATH 120
   Calculus of Functions of Several Variables

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Marketa Havlickova

4. Textbooks (title, author, publisher, year): Calculus: Early Transcendentals, 8th edition, by James Stewart, Cengage Learning, 2016 (Chapters 12–16).

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      Analytic geometry in three dimensions, using vectors. Real-valued functions of two and three variables, partial derivatives, gradient and directional derivatives, level curves and surfaces, maxima and minima. Parametrized curves in space, motion in space, line integrals; applications. Multiple integrals, with applications. Divergence and curl. The theorems of Green, Stokes, and Gauss.

   b. Prerequisites or co-requisites for the course: After MATH 115, or with permission of instructor. May not be taken after MATH 121.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Learn and understand how to use the following concepts:
        - Analytic geometry in three dimensions, using vectors;
        - Real-valued functions of two and three variables, partial derivatives, gradient and directional derivatives, level curves and surfaces, maxima, and minima;
        - Parameterized curves in space, motion in space, line integrals, with applications;
        - Multiple integrals, with applications;
        - Divergence and curl; and
        - The theorems of Green, Stokes, and Gauss.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Vector geometry in three dimensions; vector-valued functions and parametrized curves; scalar functions of multiple variables; partial derivatives; gradients and directional derivatives; constrained optimization; double integrals; polar coordinates; vector fields; line integrals; Green's Theorem; curl and divergence of vector fields; parametrized surface; surfaces integrals; Stokes' Theorem; triple integrals; cylindrical and spherical coordinates and the Divergence Theorem

1. Course number and name: ENAS 151/APHY 151/PHYS 151
   Multivariable Calculus for Engineers

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Beth Anne V. Bennett

4. Textbooks (title, author, publisher, year): Calculus: Multivariable, 10th edition, by Howard Anton, Irl Bivens, and Stephen Davis, John Wiley & Sons, Inc., 2012.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      An introduction to multivariable calculus focusing on applications to engineering problems. Topics include vector-valued functions, vector analysis, partial differentiation, multiple integrals, vector calculus, and the theorems of Green, Stokes, and Gauss.

   b. Prerequisites or co-requisites for the course: MATH 115 or equivalent.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Develop ability to use vector-valued functions when working with lines, planes, and surfaces.
      - Develop ability to differentiate, integrate, and apply parametric representations to vector-valued functions in order to compute physical quantities (e.g., position, velocity, and acceleration).
      - Develop ability to perform partial differentiation, including deriving the appropriate form of the Chain Rule.
      - Develop ability to perform double and triple integrals in various coordinate systems in order to compute physical quantities (e.g., average value of a function, mass, center of mass, and centroid).
      - Develop ability to apply multivariable integral theorems to vector-valued functions.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Vector geometry in three dimensions; vector-valued functions and parametrized curves; motion along a curve; scalar functions of multiple variables; partial derivatives and Chain Rule; directional derivatives and gradients; constrained optimization; double integrals; polar coordinates; triple integrals; cylindrical and spherical coordinates; average of a function over a region in 2-space and in 3-space; centers of gravity and mass; vector fields; curl and divergence of vector fields; line integrals; Green's Theorem; parametrization of surfaces; surface integrals; flux; Divergence Theorem; Stokes' Theorem

1. Course number and name: PHYS 180
University Physics I

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Adriane Steinacker

4. Textbooks (title, author, publisher, year): Fundamentals of Physics, 10th edition, by David Halliday, Robert Resnick, and Jearl Walker, John Wiley & Sons, Inc., 2013.

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      A broad introduction to classical and modern physics for students who have some previous preparation in physics and mathematics. Fall-term topics include Newtonian mechanics, gravitation, waves, and thermodynamics. Spring-term topics include electromagnetism, special relativity, and quantum physics.

   b. Prerequisites or co-requisites for the course: Concurrently with MATH 115 and 120 or equivalents. May not be taken for credit after PHYS 170, 171.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand course topics, which include Newtonian mechanics, gravitation, waves, and thermodynamics, and be able to apply them in order to solve problems.
      - Develop analytical skills to reduce a complex problem to its simplest parts.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Kinematics; motion in 2D and 3D; uniform circular motion and centripetal acceleration; relative motion; dynamics; friction and drag; energy, power, and work; collisions and momentum; center of mass and applications; rotational motion; rotational dynamics; rotational kinetic energy and angular momentum; Law of Gravity; harmonic oscillator; waves

1. Course number and name: PHYS 181
University Physics II

2. Credits and contact hours: 1.0 credits, 2.5 hours/week

3. Instructor's name: Adriane Steinacker

4. Textbooks (title, author, publisher, year): Fundamentals of Physics, 10th edition, by David Halliday, Robert Resnick, and Jearl Walker, John Wiley & Sons, Inc., 2013 (Chapters 21–33 and 34 or 37).

5. Specific course information:
   a. Brief description of the content of the course (catalog description):
      A broad introduction to classical and modern physics for students who have some previous preparation in physics and mathematics. Fall-term topics include Newtonian mechanics, gravitation, waves, and thermodynamics. Spring-term topics include electromagnetism, special relativity, and quantum physics.

   b. Prerequisites or co-requisites for the course: Concurrently with MATH 115 and 120 or equivalents. May not be taken for credit after PHYS 170, 171.

   c. Prerequisite, required, or elective course: Prerequisite

6. Specific goals for the course
   a. Specific outcomes of instruction:
      - Understand course topics, which include electromagnetism, special relativity, and quantum physics, and be able to apply them in order to solve problems.
      - Develop analytical skills to reduce a complex problem to its simplest parts.

   b. Student outcomes addressed by this course:
      SO 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

7. Brief list of topics to be covered: Charges, conductors, insulators, and electrostatic force; electric fields; electric fluc and Gauss's Law, with applications; electric potential; capacitors and capacitance; dielectrics; electric current, resistance, Ohm's Law, resistivity; RC circuits; direct current (DC) circuits; power; electromotive force (EMF); ammeter and voltmeter; magnetic field, Biot-Savart Law, with applications; Lorentz Force; discovery of the electron and elementary charge; electric motors; magnetic flux, Faraday's Law, and Lenz's Law; induction and energy transfer; LC and LR circuits; alternating current (AC) circuits; Maxwell's Equations; the speed of light

Appendix B – Faculty Vitae

SEAS Administration

- Prof. Jeffrey Brock, Dean
- Dr. Vincent Wilczynski, Deputy Dean
- Dr. Sarah Miller, Assistant Dean

Yale Chemical Engineering Ladder Faculty:

- Prof. Eric Altman
- Prof. Peijun Guo
- Prof. Amir Haji-Akbari
- Prof. Shu Hu
- Prof. Jaehong Kim
- Prof. Michael Loewenberg
- Prof. Lisa Pfefferle
- Prof. Paul Van Tassel
- Prof. T. Kyle Vanderlick
- Prof. Mingjiang Zhong

Adjunct Chemical Engineering Teaching Faculty:

- Dr. Yehia Khalil

1. Name and academic rank: Jeffrey F. Brock
Dean, School of Engineering & Applied Science,
Dean of Science, Faculty of Arts & Sciences, and
Zhao and Ji Professor of Mathematics

2. Degrees with disciplines, institutions, and dates:
Ph.D. Mathematics, University of California, Berkeley, 1997
B.A. Mathematics, Yale University, 1992

3. Academic experience with institution rank and title:
- Zhao and Ji Professor, Mathematics, Yale University, 2019–present
- Dean, School of Engineering & Applied Science, Yale University, 2019–present
- Dean of Science, Faculty of Arts & Sciences, Yale University, 2019–present
- Professor, Mathematics, Yale University, 2018–present
- Visiting Professor (Professeur invité), Université Paul Sabatier, France, 2015
- Visiting Professor (Maître de Conférence invité), Université Paul Sabatier, France, 2010
- Professor, Mathematics, Brown University, 2007–2018
- Associate Professor, Mathematics, Brown University, 2003–2007
- Visiting Professor, University of Texas, Austin, 2003–2004
- Assistant Professor, Mathematics, University of Chicago, 2000–2003
- Szegö Asst. Professor and NSF Postdoc. Fellow, Mathematics, Stanford Univ., 1997–2000

4. Non-academic experience: N/A

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: Fellow of the American Mathematical Society (AMS)

7. Honors and awards:
- Sabbatical Fellowship, Simons Foundation, 2016 (declined)
- John Simon Guggenheim Fellowship, 2008
- Donald T. Harrington Faculty Fellowship, UT Austin, 2003–2004
- Alfred P. Sloan Doctoral Dissertation Fellowship, UC Berkeley, 1996–1997
- Outstanding Graduate Student Instructor Award, UC Berkeley, 1996
- NSF Graduate Fellowship, UC Berkeley, 1993–1996

8. Service activities (within and outside Yale):
Within Yale:
- Member, Physical Sciences and Engineering Advisory Committee, 2018–present

Outside Yale:
- Editorial Board, J. Topology, 2018–present
- Scientific Advisory Board, ICERM, Brown University, 2017–present

- Member, Committee on Committees, American Mathematical Society, 2017–2018
- Director, Data Science Initiative, Brown University, 2016–2018
- Co-chair, Search Committee for ICERM Director, Brown University, 2014–2015
- Chair of Mathematics, Brown University, 2013–2017
- Deputy / Associate Director, ICERM, Brown University, 2010–2017
- Director of Undergraduate Studies of Mathematics, Brown University, 2008–2009
- Freshman Adviser, Brown University, 2005–2006
- Colloquium Chair, Mathematics, Brown University, 2004–2006
- Member of various committees at Brown University (Graduate Admissions Cmte., Tenure and Appointments Cmte., Tamarkin Asst. Professor Cmte., Senior Appointments Cmte. Undergraduate Science Education Cmte., Diversity Cmte. for Mathematics, and Steering Cmte. for Brown University Data Science Initiative), 2003–2018

9. Most important publications and/or presentations (last five years):
   - J. Brock, C. Leininger, B. Modami, and K. Rafi, "Limit sets of Teichmüller geodesics with minimal nonuniquely ergodic vertical foliation, II," J. Reine Angew. Math. **2020** (2020) 1–66.
   - J. Brock, C. Leininger, B. Modami, and K. Rafi, "Limit sets of Weil-Petersson geodesics with nonminimal ending laminations," J. Topology and Analysis **12** (2020) 1–28.
   - J. Brock, K. Bromberg, R. Canary, C. Lecuire, and Y. Minsky, "Local topology in deformation spaces of hyperbolic 3-manifolds II," Groups, Geometry, and Dynamics (2019) in press.
   - M. Bridgeman, J. Brock, and K. Bromberg, "Schwarzian derivatives, projective structures, and the Weil-Petersson gradient flow for renormalized volume," Duke Math. J. **168** (2019) 867–896.
   - J.F. Brock and K.W. Brombert, "Correction to 'On the density of geometrically finite Kleinian groups'," Acta Math. **219** (2017) 17–19.
   - K.N. Keshavamurthy, O.P. Leary, L.H. Merck, B. Kimia, S. Collins, D.W. Wright, J.W. Allen, J.F. Brock, and D. Merck, "Machine learning algorithm for automatic detection of CT-identifiable hyperdense lesions associated with traumatic brain injury," Proc. SPIE 10134, Medical Imaging 2017: Computer-Aided Diagnosis, 101342G (March 23, 2017).
   - J.F. Brock and N.M. Dunfield, "Norms on the cohomology of hyperbolic 3-manifolds," Invent. Math. **210** (2017) 531–558.
   - J. Brock and K. Bromberg, "Geometric inflexibility of hyperbolic cone-manifolds," in "Hyperbolic geometry and geometric group theory," Adv. Stud. Pure. Math. **73** (2017) 47–64.

10. Professional development activities:
    - Organizer:
      - Summer@ICERM Undergraduate Research Program, ICERM, Brown Univ., 2017
      - "Geometry and Dynamics in Surfaces and 3-Manifolds II," FRG Conference, 2009
      - "Kleinian groups and Teichmüller Theory, MSRI Program, 2007
      - "Geometry and Dynamics in Surfaces and 3-Manifolds," FRG Conference, 2007
      - "Tameness in Texas," Harrington Conference at UT Austin, 2004
    - NSF-VIGRE REU Instructor, University of Chicago, 2001, 2002 (summers)

1. Name and academic rank: Vincent Wilczynski
Deputy Dean, School of Engineering & Applied Science

2. Degrees with disciplines, institutions, and dates:

Ph.D.	Mechanical Engineering, The Catholic University of America, 1992
M.S.	Mechanical Engineering, Massachusetts Institute of Technology, 1987
M.S.	Naval Architecture and Marine Eng., Massachusetts Institute of Technology, 1987
B.S.	Marine Engineering, U.S. Coast Guard Academy, 1983

3. Academic experience with institution rank and title:
   - Deputy Dean, School of Engineering & Applied Science, Yale University, 2010–present
   - James S. Tyler Director, Center for Engineering Innovation and Design, Yale University, 2015–present
   - Dean of Engineering, U.S. Coast Guard Academy, 2008–2010
   - American Council on Education Fellowship for Academic Administration Leadership, 2006–2007
   - Chair, Mechanical Engineering, U.S. Coast Guard Academy, 2004–2008
   - Professor, Associate Professor, and Assistant Professor, Department of Engineering, U.S. Coast Guard Academy, 1992–2010

4. Non-academic experience:
   - Director, FIRST Robotics Competition, Manchester, NH: Responsible for premier industry/university/high school engineering partnership program w/$8 million budget, 40 employees, 1999–2000 (sabbatical leave from USCGA)
   - USCG Marine Safety Center Vessel Plan Reviewer: Approved construction blueprints for commercial vessels regulated by the U.S. Coast Guard, 1987–1992
   - Assistant Engineer, USCGC Decisive: Engineer, conning officer, and boarding officer for drug enforcement interdictions, 1983–1985

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: Fellow of American Society of Mechanical Engineers (ASME), American Society for Engineering Education (ASEE), American Council on Education (Fellow 2006/2007), Connecticut Academy of Science and Engineering

7. Honors and awards:
   - Connecticut Academy of Science and Engineering (elected to membership), 2012
   - U.S. Coast Guard Legion of Merit (for exemplary service as an officer & educator), 2010
   - ASME Edwin C. Church Medal (for national contributions in engineering outreach), 2005
   - ASME Distinguished Service Award (for effective leadership, prolonged and committed service, devotion, enthusiasm, and faithfulness in the Mechanical Eng. profession), 2003
   - U.S. Professor of the Year, Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education, 2001

- U.S. Coast Guard Meritorious Service Medal (for leading institutional accreditation team), 2000

8. Service activities (within and outside Yale):
   Outside Yale:
   - Vice President, ASME Center for Public Awareness, Board on Pre-College Education, 2004–2010

9. Most important publications and/or presentations (last five years):
   - V. Wilczynski, "Contributions of academic makerspaces to design education," in Design Education Today, D. Schaefer, G. Coates, and C. Eckert (eds.), Springer, 2019, 91–114.
   - V. Wilczynski, A. Wigner, M. Lande, and S. Jordan, "The value of higher education academic makerspaces for accreditation and beyond," Planning for Higher Education Journal, V46N1 (2017).
   - V. Wilczynski and A. McLaughlin, "Similarities and differences between academic centers for entrepreneurship, innovation, and making," Proceedings of the 2nd International Symposium on Academic Makerspaces, 2017.
   - V. Wilczynski and A. Hoover, "Classifying academic makerspaces: Applied at ISAM 2017," Proceedings of the 2nd International Symposium on Academic Makerspaces, 2017.
   - V. Wilczynski and M.N. Cooke, "Identifying and sharing best practices in international higher education makerspaces," ASEE International Forum, Paper ID #20789, 2017.
   - M.J. Maves and V. Wilczynski, "Higher education makerspaces: Engaged students, hands-on skills, interdisciplinary connections," Learning by Design, Spring issue (2017) 16–19.
   - P.Z. Ali, M. Cooke, M.L. Culpepper, C.R. Forest, B. Hartmann, M. Kohn, and V. Wilczynski, "The value of campus collaborations for higher education makerspaces," Proceedings of the 1st International Symposium on Academic Makerspaces, 2016
   - V. Wilczynski , J. Zinter, and L. Wilen, "Teaching engineering design in an academic makerspace: Blending theory and practice to solve client-based problems," American Society for Engineering Education Annual Conference Proceedings, 2016.
   - V. Wilczynski and R. Adrezin, "Higher education makerspaces and engineering education," Proceedings of ASME International Mechanical Engineering Conference & Exposition, 2016.
   - V. Wilczynski and S. Slezycki, FIRST Robots: Behind the Design, Chicago, IL, RRDonnelley, 2015.

10. Professional development activities:
    - Treasurer, FIRST Foundation, Manchester, NH, 2004–2014
    - Committee Member, Naval Engineering in the 21st Century, National Academy of Engineering, Transportation Review Board, Washington, DC, 2009–2011
    - NEASC Council on Institutions of Higher Education: Accreditation Member, 1996

1. Name and academic rank: Sarah Miller
Assistant Dean, School of Engineering & Applied Science

2. Degrees with disciplines, institutions, and dates:
Ph.D. Chemical & Environmental Engineering, Yale University, 2011
M.Phil. Chemical & Environmental Engineering, Yale University, 2009
M.S. Chemical & Environmental Engineering, Yale University 2007
B.S. Chemistry, Amherst College, 2003

3. Academic experience with institution rank and title:
- Assistant Dean, School of Engineering & Applied Science, Yale University, 2020–present
- Assistant Dean for Inclusive Excellence, College of Engineering & Applied Science, University of Colorado, 2014–2018
- AAAS Science Policy Fellow, National Science Foundation, Arlington, VA, 2011–2014
- Senior Administrator, Roberto Clemente School, New Haven Public Schools, 2011–2012
- Teacher, Teach for America, East Pablo Alto, CA, 2004–2006
- Dean, Green Dean Admission Office Fellowship, Amherst College, 2003–2004

4. Non-academic experience: N/A

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: N/A

7. Honors and awards:
- Chancellor's Employee of the Year, CU Boulder, 2018
- CoNECD Program of the Year, ASEE, 2018
- Advocacy Award, Chancellor's Committee for Women, CU Boulder, 2018
- NEXT Award, NCWIT, 2nd place (with Dr. R. Hoenigman and Ms. A. Parker), 2017
- CU Innovation Award, Intro to Engineering Redesign, 2015
- Pryde Distinguished Alumni Lecturer, Chemistry, Amherst College, 2013
- Elm Ivy Award, City of New Haven & Yale University, 2011
- Associates in Teaching Fellowship, Yale University, 2011
- Advanced Graduate Leadership Program (AGLP) Fellowship, School of Engineering & Applied Science, Yale University, 2009–2010
- NSF Graduate Research Fellowship, 2007–2010
- Japan Memorial Fulbright Fund, 2005

8. Service activities (within and outside Yale):
Within Yale:
- Provost Advisory Committee on Transfer Student Success, 2018–2019
- Graduate Fellow, Saybrook College, 2007–2008

Outside Yale:

- Advisory Board, National Science Foundation, 2018–2019
- Facilitator, “STEM Education and the Innovation Gender Gap,” Women in Innovation Summit, Boulder, CO, March 28, 2016
- Selection Committees at University of Colorado (Alumni Awards, Recent Alumni Award in Engineering, College of Engineering Service Award), 2014–2018

9. Most important publications and/or presentations (last five years):
   - J. Yowell, S.M. Miller, and D. Gruber, “The STEM Core Initiative: An innovative math preparation program for community college students,” National Institute for the Study of Transfer Students (NISTS) Annual Conference, Atlanta, GA, February 13–15, 2019.
   - S.M. Miller, “How to make your advisory board a win-win (and why you should have one in the first place),” Women in Leadership: Higher Education, Cambridge, MA, October 2, 2018.
   - J. Yowell and S.M. Miller, “Alignment of best practices for effective community college transfer,” NISTS Annual Conference, Atlanta, GA, February 7–8, 2018**.**
   - B. Louie, T. Ennis, C. Lammey, and S.M. Miller, “Leveraging partnerships to foster successful outcomes for students,” National Association of Multicultural Engineering Program Advocates (NAMEPA) National Conference, Blacksburg, VA, September 10–13, 2017.
   - B. Kos and S.M. Miller, “Grade-a-thons and divide and conquer: Effective assessment at scale,” American Society for Engineering Education (ASEE) Annual Conference, Columbus, OH, June 24–28, 2017.
   - S.M. Miller and C. Lammey, “How our institutions support engineers (who also happen to be parents!),” Women in Engineering ProActive Network (WEPAN) Change Leader Forum, Denver, CO, June 14–16, 2017.
   - T. Ennis, B. Myers, J. Milford, S.M. Miller, B. Louie, A. Parker, and C. Lammey, “Redshirting in engineering – The Engineering GoldShirt Program: Creating engineering capacity and expanding diversity,” First-Year Engineering Experience (FYEE) Annual Conference, Columbus, OH, July 31–August 2, 2016.
   - V. Dunn, A. Antoine, S. Swartz, and S.M. Miller, “Effects of a one-week research program on the graduate school pipeline and graduate student professional development,” ASEE Annual Conference, New Orleans, LA, June 26–29, 2016.
   - A. Parker, V. Dunn, and S.M. Miller, “Scholarships! How to do more with less,” WEPAN Change Leader Forum, Denver, CO, June 14–16, 2016.
   - A. Palmer and S.M. Miller, “Student contract to promote inclusion,” WEPAN Change Leader Forum, Denver, CO, June 14–16, 2016.
   - S.M. Miller, “Benefits of a board: How a board of external advisors can advance diversity initiatives within your university,” WEPAN Change Leader Forum, Denver, CO, June 9, 2015.
   - S.M. Miller, “What all high school girls need to know about computing,” Girls Exploring Science, Technology, Engineering, and Math Conference, Denver, CO, May 8, 2015.

10. Professional development activities:
    - Grant reviewer, National Science Foundation, 2012–2018

1. Name and academic rank: Eric Altman
Professor of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
Ph.D. Chemical Engineering, University of Pennsylvania, 1988
B.S. Chemical Engineering, Cornell University, 1983

3. Academic experience with institution rank and title:
- Director of Graduate Studies in Engineering and Applied Science, Yale Univ., 2005-2008
- Professor of Chemical Engineering, Yale University, 2002- present
- Associate Professor of Chemical Engineering, Yale University, 1998-2002
- Assistant Professor of Chemical Engineering, Yale University, 1994-1997

4. Non-academic experience:
- Postdoctoral Fellow, Office of Naval Research, 1990-1993 [Chemistry Division, Naval Research Laboratory]

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: member ACS, AIChE, AVS, and MRS.

7. Honors and awards:
- National Science Foundation Presidential Early Career Award in Science and Engineering (PECASE)
- Member Connecticut Academy of Science and Engineering
- Fellow AVS
- Office of Naval Research Postdoctoral Fellowship

8. Service activities:
- Petroleum Research Foundation Advisory Committee
- Center for Nanophase Materials Sciences Oak Ridge National Laboratory Scientific Advisory Committee
- Connecticut Academy of Sciences Zero Carbon Emissions Study Group
- AVS Surface Science Division, Chair, Programming Chair
- AVS Oxide Interfaces and Heterostructures Focus Topic Leader,
- AVS Nanoscale Science and Technology Division Vice Chair, Chair, and Programming Chair,
- President, Secretary New England Catalysis Society

9. Most important publications and/or presentations (within 5 years):
- J.-H. Jhang, J.A. Boscoboinik and E.I. Altman, “Ambient Pressure X-ray Photoelectron Spectroscopy Study of Water Formation and Adsorption Under Two-dimensional Silica

and Aluminosilicate Layers on Pd(111),” Journal of Chemical Physics **152** (2020) 084705 (invited).

- C. Zhou, X. Liang, G.S. Hutchings, J.-H. Jhang, Z.S. Fishman, R. Wu, A. Gozar, U.D. Schwarz, S. Ismail-Beigi and E.I. Altman, “Tuning Two-dimensional Phase Formation Through Epitaxial Strain and Growth Conditions: Silica and Silicate on Ni_xPd_{1-x} (111) Alloy Substrates,” Nanoscale **11** (2019) 21340.
- K. Zou, S.D. Albright, O.E. Dagdeviren, M.D. Morales-Acosta, G.H. Simon, C. Zhou, S. Mandal, S. Ismail-Beigi, U.D. Schwarz, E.I. Altman, F.J. Walker and C.H. Ahn, “Revealing Surface-state Transport in Ultrathin Topological Crystalline Insulator SnTe Films,” Applied Physics Letters Materials **7** (2019) 051106 (editor’s choice).
- J.-H. Jhang and E.I. Altman, ‘Water Chemistry on Two-dimensional Silicates Studied by Density Functional Theory and Temperature-programmed Desorption,” Surface Science **679** (2019) 99 (invited).
- X. Zhu and E.I. Altman, “Surface and Interface Properties of Polar Thin Films on a Ferroelectric Substrate: ZnO on $LiNbO_3$ (0001) and $(000\bar{1})$,” Journal of Vacuum Science and Technology A **36** (2018) 021511 (editor’s pick).
- X. Zhu, J.-H. Jhang, C. Zhou, O.E. Dagdeviren, Z. Chen, U.D. Schwarz and E.I. Altman, “Using ZnO-Cr_2O_3-ZnO Heterostructures to Characterize Polarization Penetration Depths Through Non-polar Films,” Physical Chemistry Chemical Physics **19** (2017) 3492.
- E.I. Altman, “Group III Phosphates as Two-Dimensional van der Waals Materials,” Journal of Physical Chemistry C **121** (2017) 16328.
- J.-H. Jhang, C. Zhou, O.E. Dagdeviren, U.D. Schwarz and E.I. Altman, “Growth of Two-Dimensional Silica and Aluminosilicate Bilayers on Pd(111): From Incommensurate to Commensurate Crystalline,” Physical Chemistry Chemical Physics **19** (2017) 14001.
- G.S. Hutchings, J.-H. Jhang, C. Zhou, D. Hynek, U.D. Schwarz and E.I. Altman, “Epitaxial Ni_xPd_{1-x} (111) Alloy Substrates with Continuously Tunable Lattice Constants for 2D Materials Growth,” ACS Applied Materials and Interfaces **9** (2017) 11266.
- Malashevich, S. Ismail-Beigi and E.I. Altman, “Directing the Structure of Two-Dimensional Silica and Silicates,” Journal of Physical Chemistry C **120** (2016) 26670.
- O.E. Dagdeviren, J. Götzen, E.I. Altman and U.D. Schwarz, “Exploring Site-Specific Chemical Interactions at Surfaces: A Case Study on Highly Ordered Pyrolytic Graphite,” Nanotechnology **27** (2016) 485708.
- K. Zou, S. Mandal, S.D. Albright, R. Peng, D. Kumah, C. Lau, G.H. Simon, O.E. Dagdeviren, X. He, I. Božović, U.D. Schwarz, E.I. Altman, D. Feng, F.J. Walker, S. Ismail-Beigi, and C.H. Ahn, “Role of Double TiO_2 Layers at the Interface of FeSe/$SrTiO_3$ Superconductors,” Physical Review B **93** (2016) 180506(R).
- Kakekhani, S. Ismail-Beigi, and E.I. Altman, “Ferroelectrics: A Pathway to Switchable Surface Chemistry and Catalysis,” Surface Science (Invited) **650** (2016) 302.

10. Professional development activities: N/A

1. Name and academic rank: Peijun Guo
Assistant Professor of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
Ph.D. Materials Science and Engineering, Northwestern University, 2016
M.S. Materials Science and Engineering, Northwestern University, 2011
B. S. Materials Science and Engineering, Tsinghua University, 2009

3. Academic experience with institution rank and title:
- Assistant Professor, Department of Chemical and Environmental Engineering, Yale University, 2020-present
- Enrico Fermi Named Fellow, Center for Nanoscale Materials, Argonne National Laboratory, 2017-2019
- Postdoctoral Appointee, Center for Nanoscale Materials, Argonne National Laboratory, 2016-2017

4. Non-academic experience: N/A

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: Member – Materials Research Society, American Institute of Chemical Engineers, SPIE

7. Honors and awards:
- Inventor Award of Argonne National Laboratory, 2017
- Materials Research Society Fall Meeting Graduate Student Gold Award, 2016
- SPIE Optics and Photonics Education Scholarship, 2016
- Hierarchical Materials Fellowship, 2010

8. Service activities:
- Symposium session chair, American Institute of Chemical Engineers, San Francisco, CA, 2020
- Ad hoc Reviewer for Nature Communications, Advanced Functional Materials, ACS Photonics, Optics Letters, etc.

9. Most important publications and/or presentations (within 5 years):
- P. Guo and others, “Infrared-pump electronic-probe of methylammonium lead iodide reveals electronically decoupled organic and inorganic sublattices,” Nature Communications (2019).
- P. Guo and others, “Hyperbolic dispersion arising from anisotropic excitons in two-dimensional perovskites,” Physical Review Letters (2018).
- P. Guo and others, “Slow thermal equilibration in methylammonium lead iodide revealed by transient mid-infrared spectroscopy,” Nature Communications (2018).

- P. Guo and others, “Cross-plane coherent acoustic phonons in two-dimensional organic-inorganic hybrid perovskites,” Nature Communications (2018).
- P. Guo and others, “Large optical nonlinearity of ITO nanorods for sub-picosecond all-optical modulation of the full-visible spectrum,” Nature Communications (2016).
- P. Guo and others, “Ultrafast switching of tunable infrared plasmons in indium tin oxide nanorod arrays with large absolute amplitude,” Nature Photonics (2016).

10. Professional development activities: N/A

1. Name and academic rank: Amir Haji-Akbari
Assistant Professor of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
   Ph.D. Chemical Engineering, University of Michigan, 2012
   M.S. Applied Mathematics, University of Michigan, 2009
   M.S. Chemical Engineering, University of Michigan, 2006
   B.S. Biotechnology, University of Tehran, Iran, 2003

3. Academic experience with institution rank and title:
   - Assistant Professor, Chemical & Environmental Engineering, Yale University, 2017-Present
   - Postdoctoral Research Associate, Chemical and Biological Engineering, Princeton University (2012-16)

4. Non-academic experience: N/A

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: American Institute of Chemical Engineering (AIChE), American Physical Society (APS)

7. Honors and awards:
   - AIChE COMSEF Young Investigator Award (2019)
   - NSF Early CAREER Award; Computational Design & Optimization of Operationally Robust Crystal Nucleating Materials via Surface Nano-Patterning (2018)
   - Yale Public Voices Fellow (2017-18)
   - Distinguished Young Scholar Seminar Series, Department of Chemical Engineering, University of Washington (2014)
   - Rackham Predoctoral Fellowship, University of Michigan (2010)

8. Service activities:
   - AIChE Area 1A Programming Committee (2017-2020).

9. Most important publications and/or presentations (within 5 years):
   - Malmir H, Epsztein R, Elimelech M, Haji-Akbari A, “Induced Charge Anisotropy: a Hidden Variable Affecting Ion Transport through Membranes”, **Matter**, 2: 735 (2020).
   - Feng X, Kawabata K, Cowan MG, Dwulet GE, Toth K, Sixdenier L, Haji-Akbari A, Noble RD, Elimelech M, Gin DL, Osuji CO , “Single Crystal Texture in a Soft Mesophase by Directing Molecular Assembly along Dual Axes”, **Nat. Mater**, 18: 1235 (2019).
   - Haji-Akbari A, “Forward Flux Sampling with Jumpy Order Parameters”, **J. Chem. Phys.**, 149: 072303 (2018).
   - Palmer JC, Haji-Akbari A, Singh RS, Martelli F, Car R, Panagiotopoulos AZ, Debenedetti PG, “*Comment on “The Putative Liquid*-Liquid Transition is a Liquid-Solid Transition in

Atomistic Models of Water", [Parts I and II: J. Chem. Phys., 135, 134503 (2011); J. Chem. Phys., 138: 214504 (2013)]", **J. Chem. Phys.**, 148: 137101 (2018).

- Haji-Akbari A, Debenedetti PG, "Computational Investigation of Surface Freezing in a Molecular Model of Water", **PNAS**, 114: 3316 (2017).
- Altabet YE, Haji-Akbari A, Debenedetti PG, "Effect of Material Flexibility on the Thermodynamics and Kinetics of Hydrophobically-Induced Evaporation of Water ", **PNAS**, 114: E2548 (2017).
- Haji-Akbari A, "Rating Antifreeze Proteins: Not a Breeze", **PNAS**, 113: 3714 (2016).
- Haji-Akbari A, Debenedetti PG, "Direct Calculation of Ice Homogeneous Nucleation Rate for a Molecular Model of Water", **PNAS**, 112: 10582 (2015).

10. Professional development activities:
    - Yale Public Voices Fellowship Program (2017-18).

1. Name and academic rank: Shu Hu
Assistant Professor of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
Ph.D. Materials Science & Engineering, Stanford University, 2011
Ph.D. minor Management Science & Engineering, Stanford University, 2011
M.S. Materials Science & Engineering, Stanford University, 2008
B.S. Materials Science & Engineering, Tsinghua University, 2006

3. Academic experience with institution rank and title:
- Assistant Professor, Chemical & Environmental Engineering, Yale University 2016 – Present
- Faculty Affiliate, Energy Science Institute, Yale West Campus

4. Non-academic experience:
- Consultant, Green Energy Consulting, California, 2010
- Assistant Engineer, China Battery Company (CBAT), 2009
- Research and Development Intern, Nanosolar Inc., California, 2008

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: American Institute of Chemical Engineers, American Chemical Society, Electrochemical Society, Materials Research Society, American Association for the Advancement of Science, the Minerals, Metals & Materials Society (TMS)

7. Honors and awards:
- Scialog Fellow, Research Corporation and the Sloan Foundation, 2019
- Electrochemical Society, Division Young Investigator Award, 2019
- Royal Society of Chemistry, JMCA, Emerging Investigators, 2018
- Materials Research Society Graduate Student Gold Award, 2011
- Ross N. Tucker Award, the Minerals, Metals & Materials Society, 2011
- Stanford Graduate Fellowship, 2007
- Stanford School of Engineering Fellowship, 2006

8. Service activities:
- Session chair, AICHE meeting, Chemical Reaction Engineering, Particle Technology Forum, and Nanoscale Science & Engineering Forum, 2016 — Present
- Moderator, Advanced Water Splitting Materials (AWSM) Working Group, US Department of Energy, EERE, Vehicle Technology Office, 2017 — Present
- Energy Sciences Institute Advisory Board, Yale University, 2016 — Present
- Yale West Campus Cleanroom & Nanofabrication Facility Committee, 2017 — Present
- Yale West Campus Materials Characterization Core Committee, 2016 — Present

- Yale West Campus Imaging Core Committee, 2017 — Present
- Proposal panelist, NSF Catalysis and Bio-catalysis Program (CBET), ACS Petroleum Research Fund (PRF), DOE, BES, EERE, German Science Foundations (DFG) cluster proposal for solar fuels, and Swiss Science Foundation

9. Most important publications and/or presentations (within 5 years):
    - Xiangyan Chen, Xin Shen, Shaohua Shen, Matthew O. Reese, and Shu Hu, "Stable CdTe Photoanodes with Energetics Matching to Coating Intermediate Band", **ACS Energy Letters**, 5, 1865 (2020). doi: 10.1021/acsenergylett.0c00603
    - Zhenhua Pan, Yanagi Rito, Qian Wang, Xin Shen, Qianhong Zhu, Yudong Xue, Jason A. Rohr, Takashi Hisatomi, Kazunari Domen, and Shu Hu, "Mutually-dependent kinetics and energetics of photocatalyst/co-catalyst/two-redox liquid junctions", **Energy & Environmental Science**, 13, 162–173 (2019). doi: 10.1039/C9EE02910A (2020 Energy and Environmental Science HOT Articles)
    - S. Hu, "Membrane-Less Photoelectrochemical Devices for H_2O_2 Production Enabled by Selective Water Oxidation to H_2O_2", **Sustainable Energy & Fuels**, 3, 101–114 (2019). DOI: 10.1039/C8SE00329G (Cover article for Green Chemistry focused issue)
    - G. Siddiqi, Z. Luo, Y. Xie, Z. Pan, Q. Zhu, J. A. Röhr, J. J. Cha, S. Hu, "Stable Water Oxidation In Acid Using Manganese-Modified TiO_2 Protective Coatings", **ACS Applied Materials & Interfaces**, 10, 18805–18815 (2018).
    - S. Hu, N. S. Lewis, J. W. Ager, J. McKone, N. C. Strandwitz, "Thin-Film Materials for the Protection of Semiconducting Photoelectrodes in Solar-Fuel Generators", **Journal of Physical Chemistry C**, 119, 24201 – 24228 (2015).(Invited review)

10. Professional development activities:
    - External Advisor, Center for Functional Nanomaterials, Brookhaven National Laboratory 2018 - Present

1. Name and academic rank: Jaehong Kim
Henry P. Becton Sr. Professor of Engineering and
Chair of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
Ph.D. Environmental Engineering, University of Illinois at Urbana-Champaign, 2002
M.S. Chemical & Biological Engineering, Seoul National University, 1997
B. S. Chemical & Biological Engineering, Seoul National University, 1995

3. Academic experience with institution rank and title:
2018–present Henry P. Becton Sr. Professor of Engineering, Yale
2017–present Professor, School of Public Health, Environmental Health Sciences, Yale
2017–present Professor, School of Forestry and Environmental Studies, Yale
2016–present Chair, Chemical and Environmental Engineering, Yale
2015–present Professor, Chemical and Environmental Engineering, Yale
2013–2015 Barton L. Weller Associate Professor, Chemical and Environmental Eng., Yale
2013–2015 Adjunct Professor, School of Civil and Environmental Eng. (CEE), Georgia Tech
2012–2013 Associate Chair for Undergraduate Programs, School of CEE, Georgia Tech
2013–2013 Georgia Power Distinguished Professor, School of CEE, Georgia Tech
2012–2013 Georgia Power Distinguished Associate Professor, School of CEE, Georgia Tech
2009–2012 Carlton S. Wilder Associate Professor, School of CEE, Georgia Tech
2009–2013 Associate Professor with Tenure, School of CEE, Georgia Tech
2002–2009 Assistant Professor, School of CEE, Georgia Tech

4. Non-academic experience: N/A

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: American Chemical Society (ACS), Association of Environmental Engineering and Science Professors (AEESP)

7. Honors and awards:
2018 First Runner-Up, Environmental Science & Technology 2017 Top Envir. Tech. Paper
2017 One of the Most Prolific Authors, ACS Photonics, ACS
2017 One of the Most Prolific Authors, Environmental Science & Technology Letters, ACS
2016 ACS Editors' Choice, Environmental Science & Technology Letters
2016 Elected Member, Connecticut Academy of Science and Engineering
2013 Walter L. Huber Civil Engineering Research Prize, Amer. Soc. of Civil Engs. (ASCE)
2012 Environmental Science & Technology 2011 Top Environmental Tech. Paper Award
2010 Environmental Engineering Faculty Award, AEES at Georgia Tech
2010 Bill Shultz Sabbatical Award, School of CEE, Georgia Tech
2009 Paul L. Busch Award, Water Environment Research Foundation (WERF)
2009 Excellence in Research Award, School of CEE, Georgia Tech
2007 Excellent Paper Presentation Award, Korean Society of Environmental Engineers
2002 Engelbrecht Graduate Fellowship in Environmental Engineering, UIUC

2001 Mavis Memorial Fund Scholarship, College of Engineering, UIUC

8. Service activities:
Associate Editor, ACS ES&T Engineering, Mar. 2020 - present
Editorial Advisory Board, Environmental Science & Technology Letters, Mar. 2015 - Present
Associate Editor, ASCE Journal of Environmental Engineering, Mar. 2012 – Feb. 2015
Associate Editor, Water Research, Aug. 2008 – Jul. 2012
Conference Chair, 2015 Association of Environmental Engineering and Science Professors (AEESP) Research and Education Conference, Yale University, June 2015
Member, West Campus Materials Characterization and Core Advisory Cmte., 2018 – present
Member, Provost's Advisory Committee on International Affairs, Yale, 2018 – present
Member, Yale Laboratory Safety Committee, Yale, 2017 – present
Member, Standing Advisory and Appointments Committee for F&ES, Yale 2016 - present
Member, Energy Sciences Institute Advisory Committee, Yale, 2016 – present
Member, Science and Engineering Chairs Committee (SECC), Yale, 2016 – present

9. Most important publications and/or presentations (within 5 years):

- Wei, H.; Loeb, S.K.; Halas, N.J.; Kim, J.H. "Plasmon-Enabled Degradation of Aqueous Organic Micropollutants by Janus Gold Nanorods." Proc. National Acad. Sciences, in press
- Lee, J.S.; von Gunten, U.; Kim, J.H. "Persulfate-based Advanced Oxidation: Critical Assessment of Opportunities and Roadblocks." Environmental Science & Technology, 2020, 54, 3064-3081
- Chu, C.; Zhu, Q.; Pan, Z.; Gupta, S.; Huang, D.; Du, Y.; Weon, S.; Wu, Y.; Muhich, C.; Stavitski, E.; Domen, K.; Kim, J.H. "Spatially Separating Redox Centers on 2D Carbon Nitride with Cobalt Single Atom for Photocatalytic H_2O_2 Production." Proceedings of the National Academy of Sciences, 2020, 117, 6376-6382
- Chu, C.; Yang, J.; Huang, D.; Li, J.; Wang, A.; Alvarez, P.J.J.; Kim, J.H. "Cooperative Pollutant Adsorption and Persulfate-Driven Oxidation on Hierarchically-Ordered Porous Carbon." Environmental Science & Technology, 2019, 53, 10352-10360
- Loeb, S.K.; Kim, J.; Jiang, C.; Early, L.S.; Wei, H.; Li, Q.; Kim, J.H. "Nanoparticle Enhanced Interfacial Solar Photothermal Water Disinfection Demonstrated in 3-D Printed Flow-Through Reactors." Environmental Science & Technology, 2019, 53, 7621-7631
- Chu, C.; Huang, D.; Zhu, Q.; Stavitski, E.; Spies, J.A.; Pan, J.A.; Mao, J.; Xin, H. L.; Schmuttenmaer, C.A.; Hu, S.; Kim, J.H. "Electronic Tuning of Metal Nanoparticles for Highly Efficient Photocatalytic Hydrogen Peroxide Production." ACS Catalysis, 2019, 1, 626-631
- Loeb, S.K.; Alvarez, P.J.J.; Brame, J.A.; Cates, E.L.; Choi, W.; Crittenden, J.; Dionysiou, D.D.; Li, Q.; Li-Puma, G.; Quan, X.; Sedlak, D.L.; Waite, T.D.; Westerhoff, P.; Kim, J.H. "The Technology Horizon for Photocatalytic Water Treatment: Sunrise or Sunset?" Environmental Science & Technology, 2019, 53, 2937-2947 (Cover of the Issue)

10. Professional development activities: N/A

1. Name and academic rank: Michael Loewenberg
Professor of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
Ph.D. Chemical Engineering, California Institute of Technology, 1988
B.S. Chemical Engineering, Purdue University, 1982

3. Academic experience with institution rank and title:
- Professor, Department of Chemical Engineering, Yale University 2003-present
- Associate Professor, Department of Chemical Engineering, Yale University 2000-2003
- Assistant Professor, Department of Chemical Engineering, Yale University 1995-2000

4. Non-academic experience: N/A

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: American Institute of Chemical Engineering, American Physical Society

7. Honors and awards:
- Elected Distinguished Fellow of the International Engineering and Technology Institute, 2019
- Presidential Early Career Award for Scientists and Engineers (PECASE) for "novel research on viscous multiphase fluids leading to the development of predictive models for use in the chemical and manufacturing industries," 1999
- CAREER award, National Science Foundation, 1996
- Graduate Mentor Award, Yale University, 2003

8. Service activities:
- NSF review panel, Fluid Mechanics, Particulate and Multiphase Flows, Interfacial Phenomena
- ABET Advisory Committee, West Point Academy, 2009-2011
- Director of Graduate Studies in Chemical Engineering, Yale University, 2011
- Director of Undergraduate studies in Chemical Engineering, Yale University, 1997-2008, 2009-2010, 2012-2020

9. Most important publications and/or presentations (within 5 years):
- Singha, S, Malipeddi, AR, Zurita-Gotor, M, Sarkar, K, Shen, K, Loewenberg, M, Migler, KB, Blawzdziewicz, J. 2019, Mechanisms of spontaneous chain formation and subsequent microstructural evolution in shear-driven strongly confined drop monolayers, Soft Matter, **15**, 4873-4889
- Berman, JD, Randeria, M, Style, RW, Xu, Q, Nichols, JR, Duncan, AJ, Loewenberg, M, Dufresne, ER, Jensen, KE. 2019, Singular dynamics in the failure of soft adhesive contacts, Soft Matter, **15**, 1327-1334.

- Buttacci, JD, Loewenberg, M, Roberts, CC, Nemer, MB, Rao, RR. 2017, Criteria for drop generation in multiphase microfluidic devices, Physical Review E, **95**, Article 063103.
- Kaufman, G, Mukhopadhyay, S, Rokhlenko, Y, Nejati, S, Boltyanskiy, R, Choo, Y, Loewenberg, M, Osuji, CO. 2017, Highly stiff yet elastic microcapsules incorporating cellulose nanofibrils, Soft Matter, **13**, 2733-2737.

10. Professional development activities:
    - ABET Fundamentals of Assessment Workshop, Baltimore 2019

1. Name and academic rank: Lisa D. Pfefferle
C. Baldwin Sawyer Professor of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
Ph.D. Chemical Engineering, U. of Pennsylvania (Professor S. Churchill) 1984
BSE Chemical Engineering, Princeton University 1976

3. Academic experience with institution rank and title:
- Chair, Department of Chemical Engineering, Yale University, 1999-2002
- Chair of the Science Chairs 2001-2002
- Professor of Chemical Engineering, Yale University, 1997 – present
- Assistant/Associate Professor, Chemical Engineering, Yale University, 1983-1996.

4. Non-academic experience:
- Process Supervisor and Technical Engineer, E.I. Dupont de Nemours 1976-1978

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations:
- American Institute of Chemical Engineers
- Combustion Institute

7. Honors and awards:
- CT Women of Innovation Category Winner: Research Innovation and Leadership
- Executive Committee Eastern States Combustion Institute 1996-2006
- IBM Faculty Award (for advances in carbon nanotube synthesis) 2005
- Best Paper Award, 1996 AIChE Annual Meeting
- NSF, Presidential Young Investigator
- Lilly Teaching Award, Junior Faculty Fellowship, and C.A. Lindbergh Award

8. Service activities:
- 2001-2002 Chair of the Science Chairs
- Course of Studies committee Chair
- We host local high school students in our laboratories.
- We have formed a consortium of researchers from non-PhD granting universities to participate in our research.

9. Most important publications and/or presentations (within 5 years):
- Das DD, John, P., McEnally, CS, Kim, S., Pfefferle, LD, “Measuring and predicting sooting tendencies of oxygenates, alkanes, alkenes, cycloalkanes, and aromatics on a unified scale,” Combustion and Flame 2018, vol. 190, 349-364

- He, Y. L., Fishman, Z. S., Yang, K. R., Ortiz, B., Liu, C. L., Goldsamt, J., Batista, V. S. and Pfefferle, L. D. "Hydrophobic CuO Nanosheets Functionalized with Organic Adsorbates" J. of the American Chemical Society , 2018, Vol. 140(5), pgs. 1824-1833.
- Fishman, Z; He, Y; Yang, K; Lounsbury, A; Zhu, J; Tran, T; Zimmerman, J; Batista, V; Pfefferle, L. "Hard templating ultrathin polycrystalline hematite nanosheets: effect of nano-dimension on CO2 to CO conversion via the reverse water-gas shift reaction," Nanoscale, 2017, Vol. 9, Pages 12984-12995.
- Fishman, Z; Rudshteyn, B; He, Y; Liu, B; Chaudhuri, S; Askerka, M; Haller, G; Batista, V; Pfefferle, L. "Fundamental role of oxygen stoichiometry in controlling the band gap and reactivity of CuO nanosheets," J. of the Amer. Chem. Soc., 2016, Vol 138, Pages 10978-10985.
- Azoz, S., Exarhos, A., Marquez, A., Gilbertson, L., Nejati, S., Cha, J., Zimmerman, J., Kikkawa, J., Pfefferle, LD., " Highly conductive single-walled carbon nanotube thin film preparation by direct alignment on substrates from water dispersions", Langmuir, 2015 vol. 31 (3), 1155-1163.

10. Professional development activities:
    - Gordon Conference attendance and presentations

1. Name and academic rank: Paul Van Tassel
Professor of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
   Ph.D. Chemical Engineering, University of Minnesota, 1993
   B. S. Chemistry and Mathematics, Saint Olaf College, 1987

3. Academic experience with institution rank and title:
   - Department Chair, Chemical and Environmental Engineering, **Yale University**, 2010-2016
   - Professor, **Yale University**, Chemical and Environmental Engineering, 2010-present
   - Professor, **Yale University**, Chemical Engineering, 2007-2010
   - Associate Professor**, Yale University**, Chemical Engineering, 2003-2006
   - Associate Professor, Chemical Engineering and Materials Science, **Wayne State University**, 2001-2002
   - Assistant Professor, Chemical Engineering and Materials Science**, Wayne State University**, 1996-2001

4. Non-academic experience:
   - Scientific Consultant, **Nu Angle Ltd,** Cambridge, UK
   - Scientific Consultant, **Tricardia, LLC,** Minneapolis, MN
   - Scientific Collaborator, **Unilever, Inc.,** Port Sunlight, United kingdom
   - Scientific Collaborator, **IA, Inc.,** Ann Arbor, MI
   - Scientific Advisory Board, **Neomecs, Inc.,** Minneapolis, MN
   - Scientific Advisory Board, **Questar, Inc.,** Minneapolis, MN

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: N/A

7. Honors and awards:
   - Keynote Address, AIChE Annual Meeting, Area 1A (2014)
   - Connecticut Academy of Science and Engineering (2011)
   - Invited Professor, Université de Cergy-Pontoise, France (2009)
   - J. William Fulbright Scholarship, France (2006, 2019)
   - John J. Lee Associate Professorship of Chemical Engineering (2005)
   - Invited Feature Article, Journal of Colloid and Interface Science (2003)
   - National Academy of Engineering: Frontiers of Engineering (1999)
   - National Science Foundation CAREER Award (1998)

- NATO-NSF Post-Doctoral Fellowship
- Chateaubriand Post-Doctoral Fellowship
- Enrico Fermi Summer School of Physics Scholarship
- University of Minnesota Graduate School Doctoral Dissertation Fellowship
- Alpha Chi Sigma Award

8. Service activities:
   - Yale University Faculty of Arts and Sciences Senate, 7/19-6/21.
   - Director of Graduate Studies, Dept. of Chemical and Environmental Eng., Yale, 7/17-present
   - Discussion Leader, Perspectives on Science and Engineering, 1/14-5/14
   - Seminar Leader, Yale-New Haven Teachers Institute, 1/12-7/12.
   - Committee on Majors, Yale University, 9/11-5/15 (co-Chair, 9/12-5/15).
   - Advancement Cmte. for Engineering, School of Eng. & Applied Science, Yale, 1/11-6/16.
   - Chair of Dept. of Chemical and Environmental Engineering, Yale University, 7/10-6/16.
   - Physical Sciences and Engineering Tenure and Appointments Committee, Yale, 9/09-5/10.
   - Organizer, "ACS Symposium on Engineering the Cell-Material Interface", American Chemical Society Annual Meeting, 3/10.
   - Director of Undergraduate Studies, Dept. of Chemical Engineering, Yale, 7/08-6/10.

9. Most important publications and/or presentations (within 5 years):
   - "Repulsion between oppositely charged rod-shaped macromolecules: Role of overcharging and ionic confinement," H. Antila, P. R. Van Tassel, and M. Sammalkorpi, Journal of Chemical Physics, 2017, <u>147</u>, 124901.
   - "Fibronectin-based multilayer thin films," A. Gand, M. Tabuteau, C. Chat, G. Ladam, H. Atmani, P. R. Van Tassel, and E. Pauthe, Colloids and Surfaces B, 2017, <u>156</u>, 313.
   - "Interaction modes between asymmetrically and oppositely charged rods," H. Antila, P. R. Van Tassel, and M. Sammalkorpi, Physical Review E, 2016, <u>93</u>, 022602.
   - "Ewald electrostatics for mixtures of point and continuous line charges," H. Antila, P. R. Van Tassel, and M. Sammalkorpi, Journal of Physical Chemistry B, 2015, <u>119</u>, 13218.
   - "Nanofilm biomaterials: dual control of mechanical and bioactive properties," E. Pauthe and P. R. Van Tassel, <u>Layer-by-layer films for biomedical applications</u> (Wiley-VCH), 2015, 79.
   - "Size-selective, non-covalent dispersion of carbon nanotubes by pegylated lipids: a coarse-grained molecular dynamics study," J. Maatta, V. Sampsa, P. R. Van Tassel, and M. Sammalkorpi, Journal of Chemical and Engineering Data, 2014, <u>59</u>, 3080.
   - "Nanotemplated polyelectrolyte films: toward a porous biomolecular delivery system," A. Gand, M. Hindie, D. Chacon, P. R. Van Tassel, and E. Pauthe, BioMatter, 2014, <u>4</u>, e28823.
   - "Layer-by-layer films as biomaterials: bioactivity and mechanics," E. Pauthe and P. R. Van Tassel, Journal of Biomaterials Science – Polymer Edition, 2014, <u>25</u>, 1489.

10. Professional development activities: N/A

1. Name and academic rank: T. Kyle Vanderlick
Dean Emeritus, School of Engineering & Applied Science,
Thomas E. Golden Professor of Engineering

2. Degrees with disciplines, institutions, and dates:
   Ph.D. Chemical Engineering, University of Minnesota, 1988
   M.S. Chemical Engineering, Rensselaer Polytechnic Institute, 1983
   B.S. Chemical Engineering, Rensselaer Polytechnic Institute, 1981

3. Academic experience with institution rank and title:
   - Thomas E. Golden Professor, Engineering, 2008–present
   - Dean, School of Engineering & Applied Science, Yale University, 2008–2017
   - Associate Dean for Academic Affairs, School of Engineering & Applied Sciences, Princeton University, 2003–2004
   - Professor, Chemical Engineering, Princeton University, 1998–2007
   - Associate Professor, Chemical Engineering, University of Pennsylvania, 1995–1998
   - Assistant Professor, Chemical Engineering, University of Pennsylvania, 1989–1995

4. Non-academic experience:
   - Visiting Scientist, Complex Fluids Laboratory, Rhone-Poulenc, 1997
   - NATO Postdoctoral Fellow, Universität Mainz, West Germany, 1988–1989
   - Industrial Trainee Fellow, Proctor & Gamble, 1981

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: American Institute of Chemical Engineers (AIChE), American Physical Society (APS)

7. Honors and awards:
   - John Quinn Lecturer, University of Pennsylvania, Dept. of Chemical Engineering, 2010
   - Ethel Z. Casassa Memorial Lecturer, Carnegie Mellon, Dept. of Chemical Engineering, 2006
   - Grace Hopper Lecturer, University of Pennsylvania, Dept. of Chemical Engineering, 2002
   - President's Award for Distinguished Teaching, Princeton University, 2002
   - Princeton Engineering Council Teaching Award, 2002
   - Van Ness Lecturer, Rensselaer Polytechnic Institute, Dept. of Chemical Engineering, 1997
   - Philip's Lecturer, Haverford College, Dept. of Physics, 1996
   - Class of 1942 Endowed Term Chair, University of Pennsylvania, 1995
   - S. Reid Warren, Jr. Award for Distinguished Teaching, 1994
   - Christian R. and Mary F. Lindback Foundation Award for Excellence in Teaching, 1993
   - David and Lucile Packard Fellowship, 1991
   - Presidential Young Investigator Award, 1989
   - NATO Postdoctoral Fellowship in Science and Engineering, 1988–1989

8. Service activities (within and outside Yale):

Outside Yale:

- External reviewer for various programs:
  - Schmidt Science Fellows Program, 2019–2020
  - Dept. of Chemical and Biomolecular Engineering, UC Berkeley, 2013
  - Thayer School of Engineering, Dartmouth College, 2012
  - School of Chemical and Biomolecular Engineering, Cornell University, 2012
  - Dept. of Chemical Engineering, University of Buffalo, 2008
  - Dept. of Chemical Engineering, UC Santa Barbara, 2008
  - School of Chemical Engineering, Purdue University, 2007
  - School of Chemical and Biomolecular Eng., Cornell University, 2003
- Advisory Council, Dept. of Chemical Engineering, University of Delaware, 2007–2012
- Visiting Committee, Dept. of Chemical and Biomolecular Engineering, Johns Hopkins, 2007–2011
- Technical Advisory Panel, HelioVolt Corporation, 2006
- Chair of Chemical Engineering, Princeton University, 1994–2000

9. Most important publications and/or presentations (last five years):

- F. Carle, K. Bai, T.K. Vanderlick, and E. Brown, "Development of magnetic liquid metal suspensions for magnetohydrodynamics," Phys. Rev. Fluids **2** (2017) 1–20.
- N. Dogra, H. Izadi, and T.K. Vanderlick, "A motile bacteria-based system for liposome cargo," Nature Scientific Reports **6** (2016) 1–9.
- H. Izadi, H. Dogra, F. Perreault, C. Schwarz, S. Simon, and T.K. Vanderlick, "Removal of particulate contamination from solid surfaces using polymeric micropillars," Applied Materials and Interfaces **8** (2016) 16967–16978.

10. Professional development activities: N/A

1. Name and academic rank: Mingjiang Zhong
Assistant Professor of Chemical and Environmental Engineering and Chemistry

2. Degrees with disciplines, institutions, and dates:
Ph.D. Chemistry, Carnegie Mellon University, 2013
M.S. Chemistry, Carnegie Mellon University, 2011
B.S. Chemistry, Mathematics, and Applied Mathematics, Peking University, 2008

3. Academic experience with institution rank and title:
- Assistant Professor, Chemistry, Yale University, 2020–present
- Assistant Professor, Chemical and Environmental Engineering, Yale University, 2016–present
- Postdoctoral Fellow, Chemical Engineering and Department of Chemistry, Massachusetts Institute of Technology, 2013–2016

4. Non-academic experience: N/A

5. Certifications or professional registrations: N/A

6. Current membership in professional organizations: Member – American Institute of Chemical Engineers, American Chemical Society

7. Honors and awards:
- 3M Non-Tenured Faculty Award, 2020
- RSC Polymer Chemistry Emerging Investigator, 2019
- National Science Foundation CAREER Award, 2019
- ACS PMSE Young Investigator, 2019
- ACS Petroleum Research Fund Doctoral New Investigator, 2017
- Guy C. Berry Graduate Research Award, Carnegie Mellon University, 2013
- Chinese Government Award for Outstanding Self-Financed Students Abroad, 2013
- ACS POLY Award for Excellence in Graduate Polymer Research, 2013
- ACS Travel Grants, ACS Pittsburgh Section, 2012
- Astrid and Bruce McWilliams Fellowship, Carnegie Mellon University, 2012

8. Service activities:
- Reviewer for the following journals: ACS Applied Materials & Interfaces, ACS Macro Letter, ACS Nano, Advance Functional Materials, Angewandte Chemie, Chemical Communications, Chemistry of Materials, Chemical Reviews, Chemical Science, Dalton, J. Petroleum Science and Engineering, J. Polymer Science, Part A: Polymer Chemistry, J. American Chemical Society, Macromolecules, Nano Research, Nanoscale, Nature Communications, Organic Chemistry Frontiers, Polymer, Polymer Chemistry, Progress in Polymer Science, RSC Advances, J. Organic Chemistry, Trends in Chemistry.
- Reviewer and panelist for NSF Divisions of Materials Research and Chemistry, DOE

Office of Science Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs, ACS Petroleum Research Fund, Kentucky Science & Engineering Foundation.
- Graduate admission committee for Yale chemical engineering program (2017–2020)
- Yale Dept. of Chemical and Environmental Eng. seminars committee (2018–2020)
- Yale Dept. of Chemical and Environmental Eng. faculty search committee (2019–2020)

9. Most important publications and/or presentations (within 5 years):
   - Porter, C. J.; Werber, J. R.; Ritt, C.; Guan, Y.; **Zhong, M.**; Elimelech, M., Controlled Grafting of Polymer Brush Layers from Porous Cellulosic Supports. J. Memb. Sci. **2020**, 579, 117719.
   - Fu, X.; Guo, Z.; Le, A. N.; Lei, J.; **Zhong, M.**, Synthesis and Visualization of Molecular Brush-on-Brush Based Hierarchically Branched Structures. Polym. Chem. **2020**, 270–274. Cao, S.; Le, A. N.; Chen, A.; **Zhong, M.**, Scalable Synthesis of Biocompatible Fluorescent Polymer Dots. J. Polym. Sci. Part A: Polym. Chem. **2020**, 58, 30–34.
   - Li, F.; Cao, M.; Feng, Y.; Liang, R.; Fu, X.; **Zhong, M.**, Site-Specifically Initiated Controlled/Living Branching Radical Polymerization: A Synthetic Route Toward Hierarchically Branched Architectures. J. Am. Chem. Soc. **2019**, 141, 794–799.
   - Le, A. N.; Liang, R.; **Zhong, M.**, Synthesis and Self-assembly of Mixed Graft Block Copolymers. Chem. Eur. J. **2019**, 25, 8177–8189.
   - Kopeć, M.; Lamson, M.; Yuan, R.; Tang, C.; Kruk, M.; **Zhong, M.**; Matyjaszewski, K.; Kowalewski, T., Polyacrylonitrile-Derived Nanostructured Carbon Materials. Prog. Polym. Sci. **2019**, 92, 89–134.
   - Guo, Z.; Le, A.; Feng, X.; Choo, Y.; Liu, B.; Wang, D.; Wan, Z.; Gu, Y.; Zhao, J.; Li, V.; Osuji, C.; Johnson, J. A.; **Zhong, M.**, Janus Graft Block Copolymers: A Universal Strategy Enabling Independently Tuned Nanostructures and Polymer Properties. Angew. Chem. Int. Ed. **2018**, 57, 8493–8497.
   - He, H.; Rahimi, H.; **Zhong, M.**; Mourran, A.; Luebke, D.; Nulwala, H.; Möller, M.; Matyjaszewski, K., Cubosomes from Hierarchical Self-assembly of Poly(ionic liquid) Block Copolymers. Nature Commun. **2017**, 8, 14057.
   - Gu, Y.; Kawamoto, K.; **Zhong, M.**; Chen, M.; Hore, M.; Jordan, A.; Korley, L.; Olsen, B. D.; Johnson, J. A., Semibatch Monomer Addition as a General Method to Tune and Enhance the Mechanics of Polymer Networks via Loop Defect Control. Proc. Natl. Acad. Sci. U.S.A. **2017**, 114, 4875–4880.
   - **Zhong, M.**; Wang, R.; Kawamoto, K.; Olsen, B. D.; Johnson, J. A., Quantifying the Impact of Molecular Defects on Polymer Network Elasticity. Science **2016**, 353, 1264–1268.

10. Professional development activities:
    - Associate Editor of Supramolecular Chemistry for Frontiers in Chemistry (2019–2020).
    - Session chair/co-chair at the AIChE annual meeting (2016–2019) and the ACS annual meetings (2016–2019).
    - Co-organizer for the 70th and 74th New England Complex Fluids Meetings.

1. Name and academic rank: Yehia F. Khalil
Adjunct Lecturer of Chemical and Environmental Engineering

2. Degrees with disciplines, institutions, and dates:
M.S. Environmental Management, Harvard University, 2018
M.S. Management Science & Engineering (MS&E), Stanford University, 2012
Sc.D. Management, School of Business, University of New Haven, 1997
Ph.D. Chemical Engineering, University of Connecticut at Storrs, 1992
M.S. Chemical Engineering, Massachusetts Institute of Technology (MIT), 1986
M.S. Nuclear Engineering, Massachusetts Institute of Technology (MIT), 1985
B.S. Nuclear Engineering, Massachusetts Institute of Technology (MIT), 1985

3. Academic experience with institution rank and title:
- 2017-2019: Technical Fellow, University of Oxford, United Kingdom
- 2010-2017: University of Oxford, United Kingdom
- 2019: Center for Risk Analysis, University of Cambridge, United Kingdom
- 1998-2007: Department of Nuclear Engineering, Massachusetts Institute of Technology
- 1996-1998: Visiting Research Scholar, Worcester Polytechnic Institute (WPI)
- 1994-present: Adjunct Lecturer, Chemical and Environmental Engineering, Yale University

4. Non-academic experience:
2004-present: Associate Director of Research, Raytheon Technologies Research Center (RTRC), East Hartford, CT
2010-present: Chairman and Operating, Hydrogen Technologies Program, International Energy Agency (IEA), Paris, France

5. Certifications or professional registrations:
2001 U.S. National Academy for Nuclear Training, Atlanta, GA
Engineering Supervisors Professional Certification Program
2001 U.S. Institute of Nuclear Power Operations (INPO)
Nuclear Safety
2001 Yale School of Management (SOM), Yale University, New Haven, CT
Executive Advanced program in Management Leadership

6. Current membership in professional organizations: Member – American Institute of Chemical Engineers, American Chemical Society

7. Honors and awards:
2016: United Technologies Corporation President's Award for Technical Leadership in product development.
2014: Senior Moulton Medal, Institution of Chemical Engineers (IChemE), Process Safety and Environmental Protection, London, United Kingdom.

2010: International Energy Agency, Prize for Fundamental Research in Hydrogen Safety, Essen, Germany.

8. Service activities:
2018-present: Editor-in-Chief, Hydrogen Safety Journal, the International Energy Agency (IEA).
2016-present: Subject Editor, Process Safety & Environmental Protection (PSEP), Elsevier Publisher.
2015-present: Senior Editor, J. of Environmental Engineering & Ecological Science, UK.

9. Most important publications and/or presentations (within 5 years):

- Khalil, Y.F. et al. (2020). Leak frequency analysis for hydrogen-based technology using Bayesian and Frequentist methods. Process Safety and Environmental Protection, 136, 148-156.
- Khalil, Y.F. (2019). Penetration testing tools for product security: Uncovering and mitigating vulnerability risks before exploited by cyber attackers. Invited presentation at the 2019th Cybersecurity Summit, Security Tools Track, 1200 Collins Rd NE | Cedar Rapids, Iowa (IA) 52402 USA.
- Khalil, Y.F. (2019). Role of hydrogen in a low-carbon economy: Safety considerations. Invited presentation, Workshop on Hydrogen Production with CCS, Sponsored by Électricité de France, Campus EDF Chatou, 6 Quai Watier, 78400 Chatou, France, November 4-8, 2019.
- Khalil, Y.F. (2019). New statistical formulations for determination of qualification test plans of safety instrumented systems (SIS) subject to low/high operational demands. Reliability Engineering & System Safety, 189, 196-209.
- Kodoth, M., Shibutani, T., Khalil, Y.F., and Miyake, A. (2019). Verification of appropriate life parameters in risk and reliability quantifications of process hazards. Process Safety and Environmental Protection, 127, 34-320.
- Khalil, Y.F. (2019). Sustainability assessment of solvolysis using supercritical fluids for carbon fiber reinforced polymers waste management. Sustainable Production and Consumption, 17, 74-84.
- Khalil, Y.F. (2018). Science-based framework for ensuring safe use of hydrogen as an energy carrier and an emission-free transportation fuel. Journal of Process Safety and Environmental Protection, 117, 326-340.
- Khalil, Y.F. (2018). Comparative environmental and human health evaluations of thermolysis and solvolysis recycling technologies of carbon fiber reinforced waste. Journal of Waste Management, 76, 767-778.

10. Professional development activities:
2020 Yale Faculty Teaching Academy
Completed Poorvu summer 2020 program for Yale Faculty Members

Appendix C – Equipment

Chemical Engineering Program Students benefit from a curricular laboratory experience, Chemical Engineering Laboratory and Design (CENG 412L), and from exposure to laboratory techniques and experimental apparatus in faculty research labs. The equipment noted below is Chemical Engineering Teaching Equipment within the **Greenberg Engineering Teaching Concourse**. The Teaching Concourse as a whole is described in Chapter 7.

Distillation Column Experimental Unit: Students study the distillation separation of water and ethanol using the distillation column as well as the software package ProSimPlus. The laboratory experiment involves the separation of an ethanol-water mixture. The feed solution enters the column at one of the three distinct stages. The distillation is performed near atmospheric pressure. Students study the effects of varying reflux ratio and feed inlet stage.

. **Figure C-1. Distillation Column Experimental Unit.**

Heat Transfer Experimental Unit: The heat transfer laboratory experiment teaches students about steady and unsteady state heat transfer. For the steady-state heat transfer experiments, the temperature is determined for various rates of heat flow from the center of a brass cylindrical annulus. The thermal conductivity of the material is determined and compared to literature values. For the unsteady-state heat transfer experiments, an object is immersed in a controlled temperature bath. The temperature at the center of the object is measured and compared to literature values.

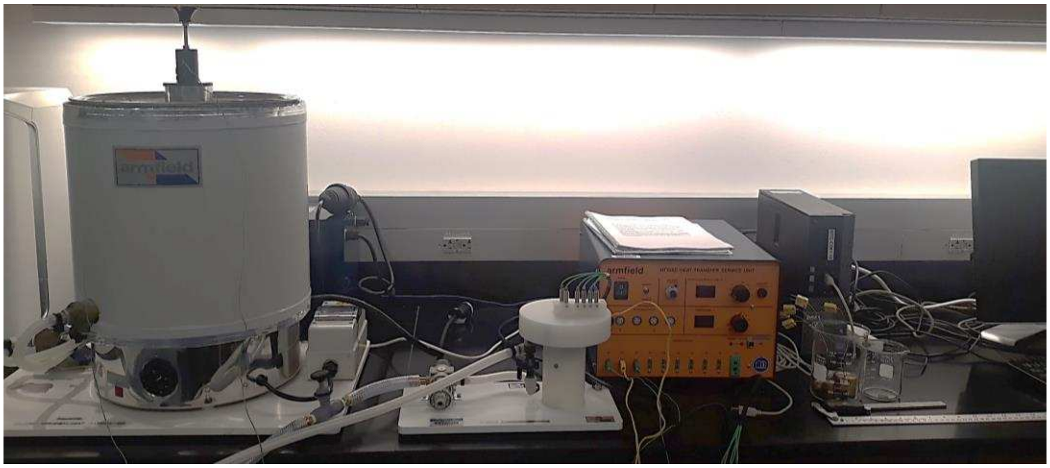

Figure C-2. Heat Transfer Experimental Unit.

Continuous Chemical Reactors Experimental Unit: The continuous chemical reactors experimental unit introduces students to the hands-on operation of different styles of chemical reactors, through obtaining residence times for each reactor and performing the saponification of ethyl acetate. The laboratory experiment examines a single stirred tank reactor, two stirred tank reactors in series, a laminar flow tubular reactor, or a plug flow tubular reactor. Students determine the concentration of the reactor on the outlet via measurements of the solution conductivity.

Figure C-3. Continuous Chemical Reactors Experimental Unit.

Membrane Separation Experimental Unit: The membrane separation laboratory experiment allows students to apply their theoretical knowledge of chemical separations by separating oxygen from air with two membrane modules. A polymeric membrane selectively permeable to oxygen is used for the separation of air into nitrogen-rich and oxygen-rich streams. Students determine the flow rate and the oxygen content using two types of membranes, flow meters, and oxygen meters. Students test each module individually as well as together in series and parallel arrangements.

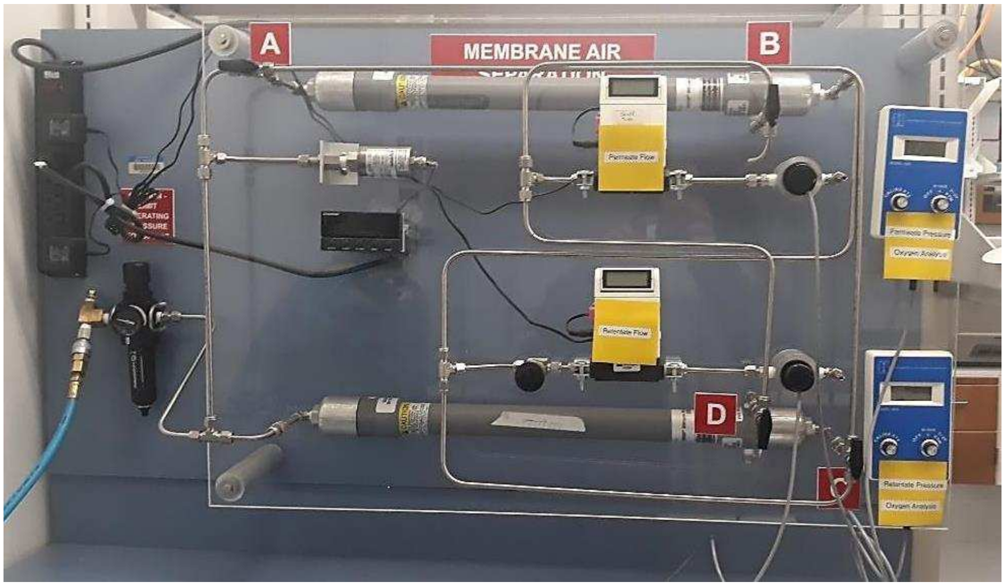

Figure C-4. Membrane Separation Experimental Unit.

Complex Fluids Experimental Unit: The complex fluids experiment introduces students to dynamic light scattering, a specialized instrument that is used in many applications of chemical engineering research. The dynamic light scattering instrument studies particle size and surface charge. A diffusive time scale serves as the basis for the measurement of the particle size. The basic principle of the complex fluids experiment is based on a laser directed toward a sample of suspension. Students explore the effects of pH and ionic strength on the stability of silica particle suspensions.

Figure C-5. Complex Fluids Experimental Unit.

Additional Equipment: Recent collaborative internships with industry (e.g., L'Oreal, Unilever) enabled students to deepen their knowledge of complex fluids by developing hair care products. The industrial mixer below was used to deflocculate products formulated by students.

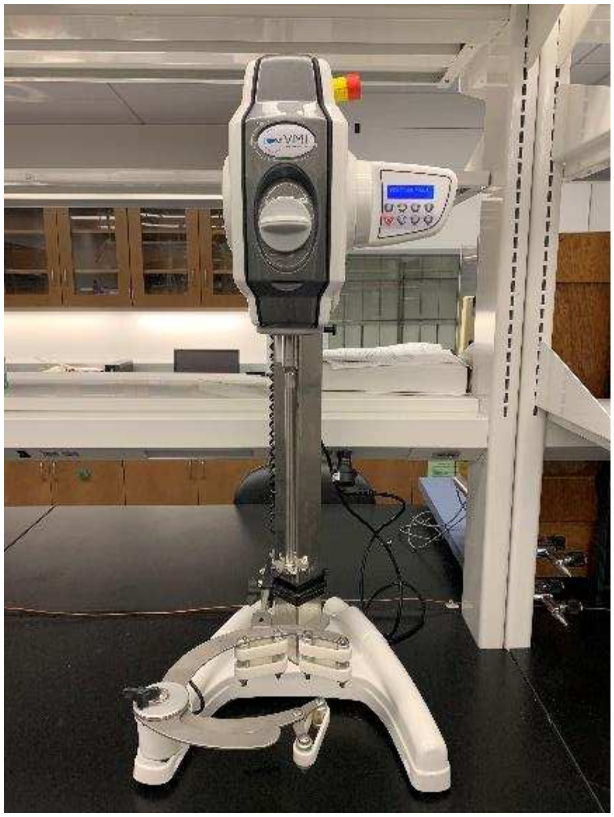

Figure C-6. Industrial mixer for deflocculation.

Environmental Applications: Total organic carbon (TOC) analyzers are a critical instrument for wastewater treatment and water quality courses and research. This TOC analyzer is available for use by chemical engineering courses that touch on these subjects.

Figure C-7. ELEMENTAR Total Organic Carbon analyzer.

Safety Equipment: To support safe experimentation, four chemical fume hoods are available in the labs used by Chemical Engineering students in the Greenberg Engineering Teaching Concourse. For biologically and environmentally focused experiments, a biosafety cabinet (class II, type A2) is available.

Figure C-8. Typical chemical hood in the Greenberg Engineering Teaching Concourse.

Figure C-9. Biosafety cabinet in the Greenberg Engineering Teaching Concourse.

Appendix D – Institutional Summary

1. The Institution

a. Name and address of the institution

Yale University
New Haven, CT

b. Name and title of the chief executive officer of the institution

Peter Salovey
President

c. Name and title of the person submitting the Self-Study Report

Jeffrey Brock
Dean, School of Engineering & Applied Science

d. Name the organizations by which the institution is now accredited, and the dates of the initial and most recent accreditation evaluations.

Yale School of Engineering and Applied Science is accredited by:
- Accreditation Board for Engineering and Technology ABET – Engineering Accreditation Commission

Initial Accreditation:
- 1936–1965
- 1982–present

Most Recent accreditation evaluation:
- 2014: General Review

2. Type of Control

The type of managerial control of Yale is private, non-profit organization.

3. Educational Unit

Yale's School of Engineering & Applied Science (SEAS) consists of the Departments of Applied Physics, Biomedical Engineering, Chemical & Environmental Engineering, Computer Science, Electrical Engineering, and Mechanical Engineering & Materials Science. Chemical Engineering, Electrical Engineering, and Mechanical Engineering are ABET-accredited.

The Yale SEAS Department Chairs report to the Dean of SEAS on administrative and educational matters. Since August 2019, Jeffrey Brock has served as the Dean of SEAS. He also serves as the Dean of Science. An organizational diagram for SEAS is presented in Figure D-1.

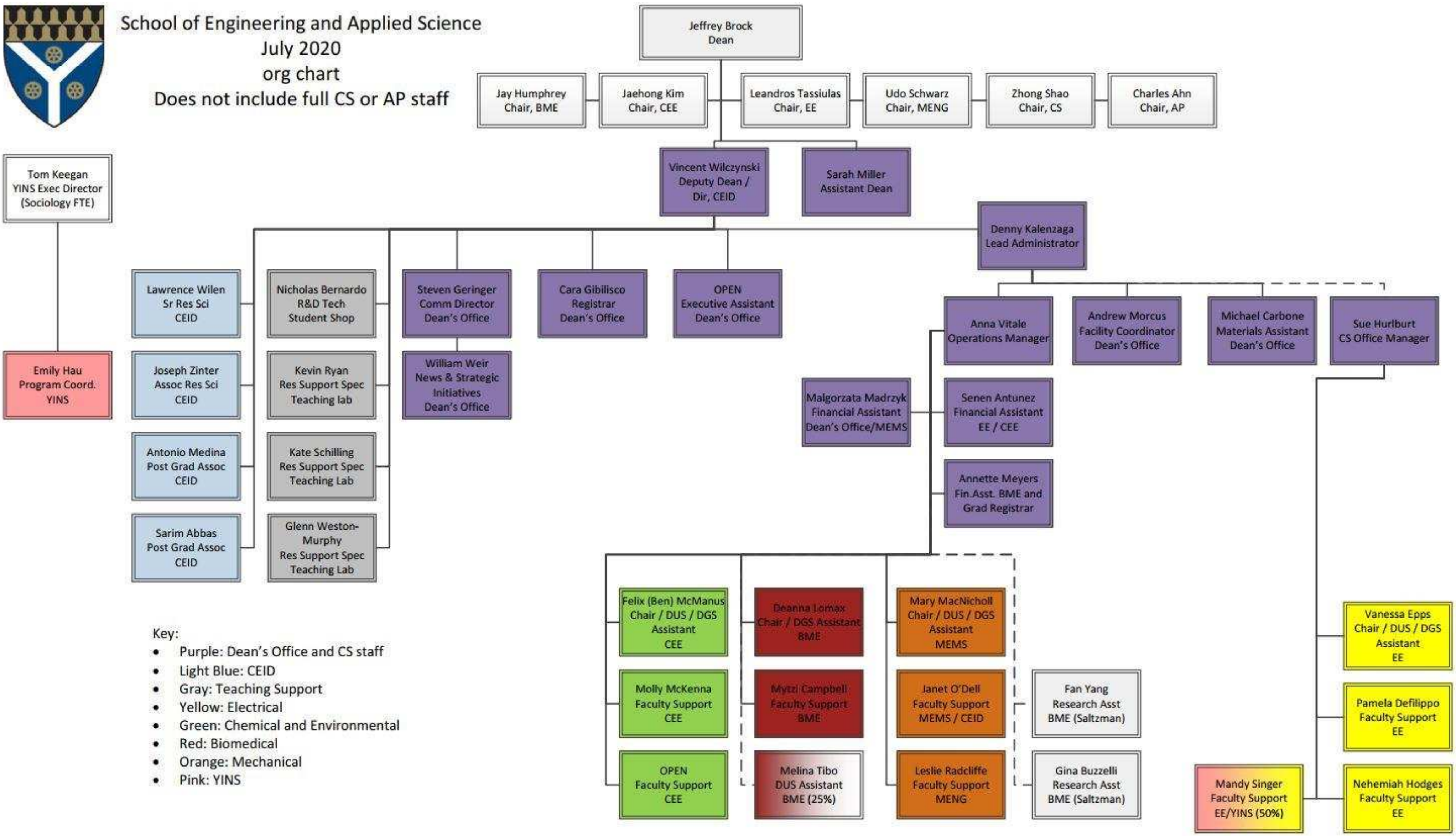

Figure D-1. Yale School of Engineering & Applied Science organizational diagram.

Yale is overseen by President Peter Salovey and the university's board of trustees, who comprise the governing and policy-making body known formally as the Yale Corporation. The institution is also led and supported by the University Cabinet, an advisory body convened by the president, which consists of the deans, vice presidents, and other senior academic and administrative leaders. Please note that Yale University no longer uses an organizational chart but rather details its structure using the following format (with direct links provided to Yale offices).

President & Trustees

- Peter Salovey, President
- Board of Trustees (The Yale Corporation)

University Cabinet

- Scott A. Strobel, Provost
- Deborah Berke, Dean, School of Architecture
- Robert Blocker, Henry & Lucy Moses Dean, School of Music
- John H. Bollier, Vice President for Facilities & Campus Development
- Jeffrey Brock, Dean, School of Engineering & Applied Science
- Nancy J. Brown, Jean and David W. Wallace Dean, School of Medicine
- James Bundy, Dean, School of Drama
- Ingrid C. "Indy" Burke, Carl W. Knobloch, Jr. Dean, School of Forestry & Environmental Studies
- Jack F. Callahan, Jr., Senior Vice President for Operations
- Kerwin K. Charles, Indra K. Nooyi Dean, School of Management
- Marvin Chun, Dean, Yale College
- Lynn Cooley, Dean, Graduate School of Arts & Sciences
- Alexander E. Dreier, Senior Vice President for Institutional Affairs, General Counsel, & Senior Counselor to the President
- Tamar Szabó Gendler, Dean, Faculty of Arts & Sciences
- Heather Gerken, Dean, Law School
- Susan Gibbons, Stephen F. Gates '68 University Librarian & Vice Provost for Collections and Scholarly Communication
- Kimberly M. Goff-Crews, Secretary & Vice President for University Life
- Ann Kurth, Dean, School of Nursing
- Marta Kuzma, Stavros Niarchos Foundation Dean, School of Art
- Pericles Lewis, Vice President for Global Strategy
- Janet E. Lindner, Vice President for Human Resources & Administration
- Stephen C. Murphy, Vice President for Finance & Chief Financial Officer
- Nathaniel Nickerson, Vice President for Communications
- Joan E. O'Neill, Vice President for Alumni Affairs & Development
- Gregory E. Sterling, The Reverend Henry L. Slack Dean, Divinity School
- David F. Swensen, Chief Investment Officer
- Sten H. Vermund, Dean, School of Public Health

Administrative Divisions - Each of Yale's vice presidents is responsible for oversight of one or more administrative offices of the university. The major subdivisions of each administrative unit are included in the listing below.

Secretary & Vice President for University Life

- Office of the Secretary and Vice President for University Life
- Chaplain's Office
- Office of LGBTQ Resources
- Student Accessibility Services

Senior Vice President for Institutional Affairs & General Counsel

- Office of General Counsel
- Office of Enterprise Risk Management
- Office of Federal and State Relations
- Office of Institutional Affairs

Senior Vice President for Operations

- Business Operations
- Office of Facilities
- Finance
- Human Resources and Administration
- Information Technology
- Office of New Haven and State Affairs
- Research Support
- Yale Hospitality

The senior vice president for operations is also responsible for the units reporting to the vice president for facilities and campus development, the vice president for finance & chief financial officer, and the vice president for human resources & administration.

- **Vice President for Alumni Affairs & Development**
  - Yale Alumni Association
  - Office of Development

- **Vice President for Communications**
  - Office of Public Affairs & Communications
  - Office of the University Printer
  - Yale Visitor Center

- **Vice President for Facilities & Campus Development**
  - Office of Facilities

- **Vice President for Finance & Chief Financial Officer**
  - Accounting & Financial Management
  - Budget Office (Financial Planning & Analysis)

- Business Solutions
  - Controller's Office
  - Financial Shared Services
  - Procurement

- **Vice President for Global Strategy**
  - Gruber Foundation
  - Office of International Affairs
  - Office of International Students & Scholars
  - Poorvu Center for Teaching and Learning
  - Stephen A. Schwarzman Center
  - Yale-NUS New Haven Office

- **Vice President for Human Resources & Administration**
  - Human Resources & Administration
  - Emergency Management
  - Public Safety
  - Travel, Relocation & Fleet
  - Yale Printing & Publishing Services

4. *Academic Support Units*

Academic Support Unit	Responsible Name	Title
Department of Chemistry	Kurt Zilm	Chair
Department of Computer Science	Zhong Shou	Chair
English	Jessica Brantley	Chair
Mathematics	Yair Minsky	Chair
Applied Physics	Charles Ahn	Chair
Physics	Karsten Heeger	Chair
Department of Electrical Engineering	Leandros Tassiulas	Chair

5. *Non-Academic Support Units*

Non-Academic Support Unit	Responsible Name	Title
Yale College	Marvin Chun	Dean of Yale College
Engineering & Applied Science Library	Andrew Shimp	Librarian for Engineering & Applied Science, Chemistry, and Mathematics
Yale Information Technology Services	John Barden	Chief Information Officer
Yale Office of Career Strategy	Jeanine Dames	Director
Tsai Center for Innovative Thinking at Yale	Claire Leinweber	Executive Director

6. Credit Unit

One semester course normally represents 2.5 class hours (three 50-minute classes or two 75-minute classes) or 3.0 laboratory hours per week. One academic semester normally represents at least 13 weeks of classes, exclusive of final examinations. One academic year normally represents two academic semesters.

7. Tables

Enrollment and Personnel details are presented in Tables D-1 and D-2 on the next two pages.

Table D-1. Program Enrollment and Degree Data.

Chemical Engineering

	Academic Year		Enrollment Year*					Total Undergrad	Total Grad	Degrees Awarded			
			1st	2nd	3rd	4th	5th			Associates	Bachelors**	Masters	Doctorates
Current Year	2019–2020	FT			18	13		31	69	N/A	8/13	4	8
		PT							1				
1 year prior to current year	2018–2019	FT			13	19		32	69	N/A	9/19	6	15
		PT							0				
2 years prior to current year	2017–2018	FT			19	14		33	75	N/A	8/14	3	10
		PT							0				
3 years prior to current year	2016–2017	FT			14	10		24	73	N/A	7/10	4	8
		PT							0				
4 years prior to current year	2015–2016	FT			10	19		29	62	N/A	14/19	4	7
		PT							1				

These are official fall term enrollment figures (head count) for the current and preceding four academic years and undergraduate and graduate degrees conferred during each of those years. The "current" year means the academic year preceding the on-site visit.

FT=full-time PT=part-time

* Yale College does not require students to declare a major until the end of their second year.
** Data reflect (BSCE) / (total of BSCE, BSES(CE)).

Table D-2. Personnel.

Department of Chemical and Environmental Engineering

Year[1]: 2019–2020

	HEAD COUNT		FTE[2]
	FT	PT	
Administrative[2]	3*	—	3*
Faculty (tenure-track)[3]	14.5**	—	14.5**
Other Faculty (excluding student assistants)	—	—	—
Student Teaching Assistants[4]	18	—	9
Technicians/Specialists	—	1	0.5
Office/Clerical Employees	3	—	3
Others[5]	—	—	—

Report data for the program being evaluated.

1. Data on this table are for the fall term immediately preceding the visit. Updated tables for the fall term when the ABET team is visiting are to be prepared and presented to the team when they arrive.
2. Persons holding joint administrative/faculty positions or other combined assignments should be allocated to each category according to the fraction of the appointment assigned to that category.
3. For faculty members, 1 FTE equals what your institution defines as a full-time load.
4. For student teaching assistants, 1 FTE equals 20 hours per week of work (or service). For undergraduate and graduate students, 1 FTE equals 15 semester credit-hours (or 24 quarter credit-hours) per term of institutional course work, meaning all courses — science, humanities and social sciences, etc.
5. Specify any other category considered appropriate, or leave blank.

* Full-time faculty members serve as the Chair, Director of Undergraduate Studies, and Director of Graduate Studies, with teaching relief allocated to these positions.

** Full-time faculty allocations were applied for the Chair, Director of Undergraduate Studies, and Director of Graduate Studies, with teaching relief allocated to these positions.

Appendix E – Lectures and Seminars Hosted by the Center for Engineering Innovation and Design

The Yale Center for Engineering Innovation and Design (CEID) regularly hosts workshops, lectures, and social events. Table E-1 contains a list of these activities for the Academic Year 2019–2020. It is noted that the on-site activities were suspended in March when remote learning was put into place. In addition to these events, the CEID staff regularly host weekly programming that includes the following events: Orientations, Laser Cutter Trainings, Makerbot Trainings, Machine Shop/Wood Shop Trainings, Sewing Machine Trainings, Mechanical Engineering Office Hours, Product Development Office Hours, and Graphic Design Office Hours. Also, the CEID serves as a venue for Networking Events hosted by the Yale Office of Career Strategy, with these events scheduled on Monday nights to provide career guidance and opportunities to meet with engineering company recruiters.

Table E-1. CEID Workshops, Lectures, and Social Events.

Date	Event Name	Presenter(s)	Event Type
8/26/19	CEID Turns 7!	CEID Staff	Social
9/4/19	Study Break: Lego Build Night	CEID Staff	Social
9/11/19	Wednesday Workshop: SolidWorks	Yale Undergraduate Aerospace Association (YUAA)	Workshop
10/2/19	Wednesday Workshop: Chocolate	CEID Staff	Workshop
10/9/19	Wednesday Workshop: Woodworking	Lior Trestman, Shop Manager of MakeHaven	Workshop
10/23/19	Wednesday Workshop: Jack-O-Lantern	CEID Staff	Workshop
10/30/19	Wednesday Workshop: Costume-Making Study Break	CEID Staff	Workshop
11/5/19	CEID Lecture Series: Kevin Tan, Founder of Snackpass	Kevin Tan, Founder of Snackpass	Lecture
11/13/19	Wednesday Workshop: Bubbles!	Dr. Lawrence Wilen, CEID Staff	Workshop
11/20/19	Wednesday Workshop: Audio Amplifier	Yale Student Branch of IEEE	Workshop

12/4/19	Winter Study Break	CEID Staff	Social
12/9/19	Grace Hopper Birthday Party	CEID Staff	Social
12/9/19	Breakfast with Disney Imagineering President	Kareem Daniel, President of Disney Imagineering	Career
12/12/19	2020 Summer Fellowship Lunch and Info Session	CEID Staff	Info Session
1/14/20	2020 Summer Fellowship Lunch and Info Session	CEID Staff	Info Session
1/15/20	CEID Blue-Booking Break	CEID Staff	Social
1/17/19	Whiteboard Art Competition	CEID Staff	Social
1/22/20	Wednesday Workshop: Basic Hand Tools	Dr. Joseph Zinter, CEID Assistant Director	Workshop
1/24/20	Make or Break: Friday Fry-yay!	CEID Staff	Social
1/29/20	Wednesday Workshop: The Science Behind Modern Art	Dr. Katherine Schilling, SEAS, and Ms. Cindy Schwarz, Yale Art Conservator	Workshop
1/31/20	Make or Break: CEID Super Bowl Party!	CEID Staff	Social
2/5/20	Wednesday Workshop: Web Development	Antonio Medina, CEID Design Fellow	Workshop
2/7/20	Make or Break: Masquerade Mask Making	CEID Staff	Social
2/12/20	Wednesday Workshop: Chocolate	CEID Staff	Workshop
2/14/20	Make or Break: Hearts and Pop Tarts	CEID Staff	Social
2/19/20	Wednesday Workshop: Concrete	CEID Staff	Workshop
2/21/20	Make or Break: Becton Turns 50!	CEID Staff	Social
2/26/20	Wednesday Workshop: Portfolios	Dr. Vincent Wilczynski, CEID Director	Workshop

2/28/20	Make or Break: Leap Year, Cinnamon Rolls, and Time Capsules!	CEID Staff	Social
3/04/20	Wednesday Workshop: Flamin’ Hot Photoshop!	Ashlyn Oakes, CEID Design Fellow	Workshop
3/06/20	Make or Spring Break	CEID Staff	Social
3/25/20	Wednesday Workshop: Web Design	Antonio Medina, CEID Design Fellow	Workshop
3/27/20	Make or Break: Origami!	CEID Staff	Social
4/01/20	Wednesday Workshop: Adobe CC Illustrator	Ashlyn Oakes, CEID Design Fellow	Workshop
4/02/20	Thursday Workshop: Fractal Art	Stefan Krastanov	Workshop
4/03/20	Make or Break: Watercolor Painting	CEID Staff	Social
4/08/20	Wednesday Workshop: TinkerCAD Circuits	Antonio Medina, CEID Design Fellow	Workshop
4/09/20	Thursday Workshop: Adobe CC Photoshop	Ashlyn Oakes, CEID Design Fellow	Workshop
4/10/20	Make or Break: Paper Airplanes	CEID Staff	Social
4/14/20	Seminar: Yale-China Art Fellowship Program Visiting Artist	Wong Chi-Yung, Visiting Artist	Seminar
4/14/20	Wednesday Workshop: Web Design with FlexBox	Sarim Abbas	Workshop
4/22/20	Wednesday Workshop: Rhino3D	Ashlyn Oakes, CEID Design Fellow	Workshop
4/23/20	Thursday Workshop: 3D Human Anatomy with Synopsys ScanIP	Dr. Steven Tommasini and Dr. Daniel Wiznia, Yale Medical School	Workshop
4/29/20	Wednesday Workshop: Analog Electronics with TinkerCAD	Antonio Medina, CEID Design Fellow	Workshop

Appendix F – Major Completion Formm

Yale College Major Clearance Form
Please sign and return by April 9, 2020

University Registrar's Office
246 Church Street, 3rd Flr.
Fax: 432-2334

1) Check the major being awarded and write in any corrections. Circle the degree being awarded if prompted.

2) If the student has already met the requirements of the major, check the first box (this is a fairly rare situation).

3) If the student has not already met the requirements of the major, check the second box. Circle the courses the student needs to pass in order to fulfill the major requirements, and add any non-course requirements, such as a noncredit senior essay or comprehensive exam. Use the "comments" section to provide details about the requirements - for example, if a student only needs to pass two out of three circled courses, or if a course cannot be taken Credit/D/Fail.

4) For students fulfilling the requirements of two majors, check that the final program matches the approved plan of study and that the student does not have more than the permitted number of overlapping courses. The recommended practice is for the departments to exchange lists of the courses each is counting toward the major .

- -

NAME: ID:

MAJOR: COLLEGE:

Other Major:

☐ This student has already completed the requirements as of the end of the last term and has nothing remaining at this time.

☐ This student has not yet completed the requirements of the major. The courses the student needs to pass and any non-course items needed to fulfill the major requirements are indicated below:

TrmYr	Subj Code	Crse Numb	Title	CR/D/F?

(continued)

Non-course requirements:

____

____

Comments:

____

____

DUS Signature	DUS Printed Name	Date

For questions contact Daria Vander Veer, Assistant University Registrar, 432-2338, daria.vanderveer@yale.edu

Appendix G – Statement of Capstone Design Project

Ethylene production via oxidative dehydrogenation (ODH) of ethane using oxygen

CENG 416 / ENVE 416 Capstone Project for Spring 2020

Capstone project developed by Dr. Yehia Khalil (CENG 416/ENVE 416 Course Instructor)

Introduction

Ethylene (C2H4) is an important building block for manufacturing of various industrial chemicals. For example, C2H4 is a fundamental chemical in the production of various important polymers including low-density polyethylene (LDPE), and high-density polyethylene (HDPE). Ethylene is also a feedstock for production of other chemicals such as polyvinyl chloride (PVC), polystyrene, and polyester. For this reason, ethylene is the most produced organic chemical in the world and its demand will soon surpass 200 million metric tons (MMt) per year (for example, its production reached 140 MMt in 2010). In the U.S., steam cracking of ethane (C2H6) is the leading technology applied for C2H4 production.

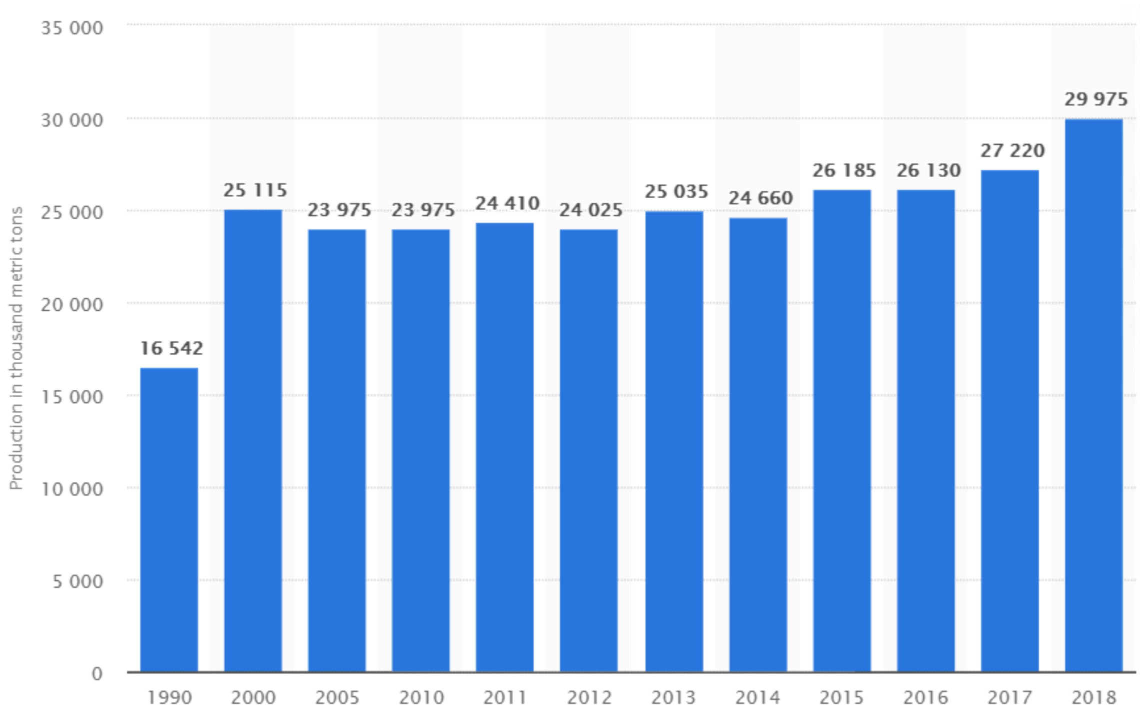

Fig. 1. U.S. ethylene production from 1990 to 2018 (in 1,000 metric tons).
Source: https://www.statista.com/statistics/974766/us-ethylene-production-volume/

Project description and objectives

The U.S. C2H4 industry has been primarily based on stream cracking of C2H6 derived from natural gas (NG). However, while the steam cracking remains the dominant technology, researchers continue to investigate other technologies such as the catalytic oxidative dehydrogenation (ODH) of C2H6 for C2H4 production.

In this gas-to-ethylene (GTE) project, you are required to design a chemical plant for ethylene production (polymer-grade purity *of* ≥ 99%) from ethane via an oxidative dehydrogenation (ODH) which uses oxygen gas and a mixed-oxide catalyst (MoVTeNb). Note that ODH chemical process runs at significantly lower temperatures than conventional steam cracking of C2H6 and, thus, providing costs and safety benefits.

Ethane is typically obtained from natural gas (C2H6 in the second highest composition after CH4 in NG). Accordingly, the plant will be located nearby in Johnson County, Texas. This location is near the extraction site of the Barnett shale gas to avoid large transportation costs of raw materials (such as C2H6 feedstock produced at the from shale gas). Please note that production of C2H6 from shale gas is out of scope of this capstone project.

Chemical reactions for ethylene production via ethane oxidative dehydrogenation

The reaction products of ODH process are: Pure ethylene (≥99%) along with water, carbon monoxide, carbon dioxide, oxygen, and unreacted ethane. Note that if air is used instead of O2, then nitrogen would be expected among the ODH process products.

Rxn-1: $C_2H_6 + 1/2\ O_2 \rightarrow C_2H_4 + H_2O$ (Primary reaction)

Rxn-2: $C_2H_6 + 7/2\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O$ (Side reaction)

Rxn-3: $C_2H_6 + 5/2\ O_2 \rightarrow 2\ CO + 3\ H_2O$ (Side reaction)

Rxn-4: $C_2H_4 + 2\ O_2 \rightarrow 2\ CO + 2\ H_2O$ (Side reaction)

ODH process description

Ethane and oxygen (from the air) are the two reactants for the process. Thermal cracking, in presence of a catalyst, leads to breaking the carbon-to-hydrogen bond (C – H) and the electrons formerly attached to the hydrogen atoms in C2H6 form double bonds between the two carbon atoms (C = C) , forming ethylene (C2H4) and the hydrogen reacts with oxygen to form water (see Rxn-1). The unreacted C2H6 should be recycled back into the ODH reactor. There are also three undesired side reactions (Rxn-2, Rxn-3, and Rnx-4) that are expected to simultaneously occur in addition to the primary (desired) reaction (Rxn-1).

The ODH reactor (should be modeled as a plug flow reactor which is kinetic-based reactor) operates at 600^{o}C and 101.3 KPa. The produced C2H4 gas must be separated from H2O by cooling the product gaseous stream to remove the condensed water followed by a pressure swing absorber

(PSA) to remove CO and CO2. Use a distillation column to remove impurities and increase C2G4 purity to ≥ 99%.

CENG 416 / ENVE 416 project teams are required to:

1) Perform a comprehensive review of the relevant literature to summarize: a) Available statistical data about U.S. ethylene production, b) Importance of ethylene as an ingredient for production of other chemicals, and c) Available technologies for ethylene production.

2) Conduct a qualitative comparative techno-economic analysis using the Pugh's decision matrix (as discussed in this course) to evaluate ODH process for ethylene production against key alternative technologies. Select the conventionally used ethylene production process as the baseline technology for benchmarking purposes in your Pugh's decision matrix. State your decision criteria (both technical and economic) to be used in the Pugh analysis.

3) Calculate the enthalpy of reaction, $(\Delta H)_R$, and Gibbs free energy change, $(\Delta G)_R$, of each of the reactions involved in the ODH process. Plot these thermodynamic parameters vs. temperature and determine an appropriate reaction temperature for this ODH process.

4) Construct a block flow diagram (BFD) for ethylene production via ODH of ethane using O2. Your PDF should include all major unit operations in this chemical process and recycle streams (as needed).

5) Use Aspen HYSYS platform to simulate the ethylene production via ODH of ethane using O2 gas. Assume that annual production capacity of the plant is 1 million metric tons (1 MMt/year) of ethylene. Obtain the mass and energy balances associated with this production plant.

6) Using Aspen HYSYS simulation, estimate the sizes of key unit operations in this plant such as the chemical reactor, distillation column, heat exchangers, etc.

7) Perform an economic analysis of the ethylene production plant and its total production cost ($/kg ethylene). Your cost analysis should take into consideration equipment depreciation over the life of the plant and 35% corporate tax rate. Assume 10 years plant life[1] and use the straight-line depreciation method as discussed in the course. Assume that the plant operates 8,040 hours/year (i.e., ≈ 92% uptime). Estimated equipment costs should be in 2020 dollars (please use the Chemical Engineering Plant Cost Index, CEPCI to account for the time value of money). Additionally, calculate the project payback period (in years) and an internal rate of return (IRR) on investment.

   Assume that the plant construction takes two years, and production begins the third year,

[1] Typically, plant life is great than 10 years. However, due to the uncertain future prices of ethane (coming from Shall Gas), the economic analysis and NPV is based a 10-years horizon.

For the economic analysis, you can use any of the tools discussed in our course, viz., the CapCost software package, Process_Design_Cost_and_Evaluation platform, or Aspen HSYSYS Economic Analyzer.

8) Based on the calculated project net present value (NPV), perform uncertainty analysis of key equipment costs and conduct sensitivity study to determine how sensitive the project NPV_{10} to key cost parameters such as ethylene price, equipment costs, utility costs, labor cost, waste treatment cost, etc.

9) Revisit your Pugh decision matrix and discuss whether ethylene production via ODH technology seems to be technically and economically more attractive compared to the alternative production technologies.

10) Instrumentation and process control – Select one of the unit operations in your process flow diagram (PFD) (e.g., heat exchangers, ODH reactor, etc.) and describe the required instrumentations and process controls.

11) Process environmental, health, and safety (EH&S) – Perform a thorough review the material safety data sheets of each of the reactants and products of the ODH process and identify associated safety issues such as flammability, explosibility, and toxicity. Address any EH&S concerns and describe how you can eliminate or mitigate the associated risks.

12) Equipment reliability and potential process risks – Apply one qualitative risk assessment (QLRA) methods discussed in the class to one of the unit operations in the ethylene production plant. For example, you could focus on potential failures of the distillation column, ODH reactor, heat exchanger, etc.

As a reminder, the QLRA methods discuss in class are as follows:

- Design failure modes & effects analysis (d-FMEA)
- Hazard and operability (HazOp) analysis
- Boolean-based fault tree analysis (FTA)

Input data

Arrhenius parameters (pre-exponential factors and activation energies) as well as the reaction orders are provided in Table 1.

Table 1. Kinetic parameters of ODH reactions.

Rxn	**Arrhenius Pre-Exponential Factor (kmol / (m^3_{cat} h $kPa^{\alpha+\beta}$)**	**Activation Energy (E*) (kJ/mol)**	**C2H6 / C2H5 Reaction Order (α) (mol/(kPa * s))**	**O2 Reaction Order (β) (mol/(kPa * s))**
Rxn-1	1.9892	119	1.50	0.13
Rxn-2	0.0277	217	1.78	0.36

Rxn	Arrhenius Pre-Exponential Factor (kmol / (m^3_{cat} h $kPa^{\alpha+\beta}$)	Activation Energy (E*) (kJ/mol)	C2H6 / C2H5 Reaction Order (α) (mol/(kPa * s))	O2 Reaction Order (β) (mol/(kPa * s))
Rxn-3	0.0386	143	1.80	0.24
Rxn-4	0.1259	242	1.33	0.30

Table 2. Utility costs.

Common Utilities	Cost
Electricity (110V – 440V)	$0.12 /kWh
Cooling water (30^{o}C – 45^{o}C)	$0.354 /GJ
Refrigerant water (15^{o}C – 25^{o}C)	$4.43 /GJ
Low pressure steam (5 barg, 160^{o}C)	$13.28 /GJ
Medium pressure steam (10 barg, 184^{o}C)	$14.19 /GJ
High pressure steam (41 barg, 254^{o}C)	$17.70 /GJ
Fuel oil (no. 2)	$14.2 /GJ
Natural Gas	$11.1 /GJ
Refrigerant 1 (5^{o}C)	$4.43 /GJ
Refrigerant 2 (-20^{o}C)	$7.89 /GJ
Refrigerant 3 (-50^{o}C)	$13.11 /GJ

Table 3. Waste disposal cost.

Waste disposal (solid and liquid)	Cost, $/ton
Nonhazardous waste	36
Hazardous waste	200

The chemical, physical and thermal properties of ethylene can be found from the following URL:

https://www.engineeringtoolbox.com/ethylene-ethene-C2H4-properties-d_2104.html

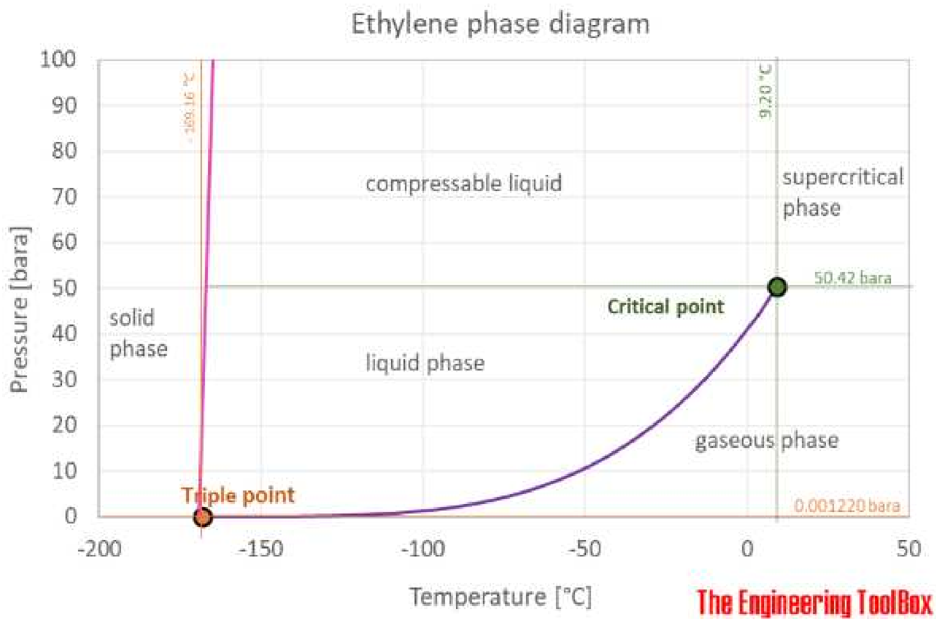

Fig. 2. Ethylene phase diagram.
Source: https://www.engineeringtoolbox.com/ethylene-ethene-C2H4-properties-d_2104.html

Table 4. Physical properties of ethylene.

Formula	C2H4
Molecular Weight (lb/mol)	28.05
Critical Temp. (°F)	49.1
Critical Pressure (psia)	742.7
Boiling Point (°F)	-154.8
Melting Point (°F)	-272.5
Psat @ 70°F (psia)	(note 1)
Liquid Density @ 70°F (lb/ft3)	(note 1)
Gas Density @ 70°F 1 atm (lb/ft3)	0.0730
Specific Volume @ 70°F 1 atm (ft3/lb)	13.70
Specific Gravity	0.992
Specific Heat @ 70°F (Btu/lbmol-°F)	10.28

Source: http://www.airproducts.com/Products/Gases/gas-facts/physical-properties/physical-properties-ethylene.aspx

Notes:
1 = Signifies at 70°F, the compound is above its critical temperature.
2 = Signifies that at 70°F, the compound is below the normal boiling point and only the equilibrium vapor is present at 1 atmosphere.

Signature Attesting to Compliance

By signing below, I attest to the following:

That Yale's Chemical Engineering Program has conducted an honest assessment of compliance and has provided a complete and accurate disclosure of timely information regarding compliance with ABET's Criteria for Accrediting Applied Science Programs to include the General Criteria and any applicable Program Criteria, and the ABET Accreditation Policy and Procedure Manual.

Jeffrey F. Brock

______________________________ **July 31, 2020**

Signature