CHEMISTRY

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The wide range of courses offered by the Department of Chemistry reflects the position of chemistry as the foundation of all the molecular sciences. In addition to graduate work in chemistry, biochemistry, or health-related disciplines, the department’s graduates find their broad scientific training useful in fields such as technology policy, business management, and law. Chemistry is an especially appropriate major for students interested in energy research or policy and the environment.

**COURSES FOR NONMAJORS WITHOUT PREREQUISITES**

The Chemistry department offers one-term courses with no prerequisites, which are intended for non-science majors. These courses do not satisfy medical-school requirements or the general-chemistry requirement for any science major. Courses for nonmajors are numbered CHEM 100–109.

**PREREQUISITES AND INTRODUCTORY COURSES**

**Prerequisite courses** Prerequisites common to all Chemistry degree programs include two terms of general chemistry and laboratory, single-variable calculus at the level of MATH 115, and one term of introductory physics numbered 170 or higher, or the equivalents in advanced placement, are prerequisite to all four degree programs. Students also are encouraged to complete a course in multivariable calculus (MATH 120 or ENAS 151).

**Introductory courses** The majority of students begin with a general chemistry sequence: either CHEM 161 and 165, or CHEM 163 and 167. Any of these courses fulfill the prerequisite for general chemistry in the Chemistry major. Students taking CHEM 161 may be taking chemistry for the first time, perhaps took chemistry as a high school sophomore, or may even have taken AP chemistry but did not fully master the subject at that level. Students in CHEM 163 will have more recently completed a year or two of chemistry in high school, although motivated students may have last taken chemistry as a high school sophomore if they have a strong math and physics background. Students who have done well in an advanced placement chemistry course or show other evidence of high achievement in science and mathematics may be given permission to start in CHEM 167. The introductory laboratory sequence is CHEM 134L and 136L; each laboratory course earns one-half course credit.

Students with a sufficiently strong background in chemistry may initiate their studies with courses in organic or physical chemistry after demonstrating proficiency on the department’s placement examination. CHEM 174 and 175 are offered expressly for first-year students. Other courses in organic chemistry, including CHEM 220 and 221, also are available to qualified first-year students. Students with a strong background in physics and calculus may be eligible for the physical-chemistry courses CHEM 332 and 333.

**PLACEMENT PROCEDURES**

**For first-year students** The Chemistry department reviews the preparation of all first-year students prior to the beginning of the fall term, using test scores, admission records, and information supplied by students. Incoming students should see the First-Year Handbook or the Chemistry department website for details on information to submit during the summer before matriculation. The department determines the appropriate general chemistry course for every entering first-year student, either CHEM 161, 163, or 167. Instructions for viewing initial placement are available on the Chemistry department website. Placements will be posted on Canvas@Yale.edu in late August.

First-year students wishing to take CHEM 174, 220, or 332, or those wishing to take a higher-level course than initially assigned, are required to take a placement examination on the first day of registration week in the fall term. Students who feel they have been placed incorrectly at too high a level may discuss changing their placement with a chemistry placement adviser and do not need to take the examination. Students uncertain about their placement are encouraged to sit for the examination, as it provides the best measure of a student’s readiness to enter the wide variety of courses offered to first-year students.

Students with placement questions, or those wishing to change their course preference indicated during preregistration, should attend the department’s orientation meeting prior to the placement examination. Additional sessions with placement advisers are scheduled throughout the first week of the fall term in 248 SCL at times listed in the Calendar for the Opening Days of College. Students wishing to change their placement should consult an adviser as soon as possible.

Students are advised to review general chemistry before taking the placement examination. They must bring a nonprogrammable, nongraphing calculator and a #2 pencil with them to the examination; cell phones may not be used. Times and places for the examination are published in the Calendar for the Opening Days of College. Shortly after the examination, students will be informed of their revised placement. For further information about placement and the examination, consult the Calendar for the Opening Days of College and the First-Year Handbook.

**Permission keys** Enrollment in any introductory chemistry course requires an electronic permission key. Keys are issued automatically by the department for entering first-year students and are displayed as green key-shaped icons next to the appropriate courses on the online...
registration page. Students are blocked from enrolling in any chemistry course for which they do not possess a permission key. Students experiencing problems with permission keys should inquire in person at the department office, 248 SCL.

For upper level students Upper level students wishing to take CHEM 161, 163, 165, or 167 should confirm their placement on Canvas@Yale by accessing the Chemistry Placement site that corresponds to their year of matriculation. If permission keys are needed, upper level students should obtain them by inquiring at the department office, 248 SCL. Those wishing to enroll in CHEM 220 may do so as long as they have satisfied the general chemistry prerequisite.

Section registration in laboratory and lecture courses Information about online registration for laboratory and discussion sections can be found in the description for each laboratory or lecture course in Yale Course Search. Due to the nature of the laboratory exercises, it is impractical to preview laboratory courses during the course selection period.

Advanced courses For the purpose of degree requirements, all DUS-approved undergraduate Chemistry courses numbered 410 or higher count as advanced lecture or laboratory courses, as do CHEM 226L, 251L, 331L, and 335L. Because most advanced courses are offered either in the fall term or have a fall-term course as a prerequisite, students should not plan to take an isolated spring-term advanced course in any given year without first consulting the DUS. Many graduate-level Chemistry courses also may count toward the advanced-course requirement; consult the DUS for information about eligible courses.

For premedical students Medical schools currently require one year of organic chemistry and laboratory as well as one year of general chemistry and laboratory. The general-chemistry requirement may be satisfied by completing CHEM 161 and 165, or CHEM 163 and 167, or two terms of physical chemistry. In most instances students with advanced placement taking only CHEM 167 may complete this requirement by taking a course in biochemistry, inorganic chemistry, or physical chemistry. Students should consult with the Office of Career Strategy for the most up-to-date premedical course advice.

REQUIREMENTS OF THE MAJOR
Four degree programs are offered: a B.A., a B.S., an intensive major leading to a B.S., and a combined B.S./M.S. The B.A. degree is intended for students who want solid training in the chemical sciences and who also intend to study other subjects in which chemical training would be an asset, such as technology policy, economics, the environment, or medicine. The B.S. degree is intended to prepare students for graduate study while permitting extensive exploration of other disciplines. The B.S. degree with an intensive major provides more focused preparation for a career in chemical research, and requires greater breadth in laboratory courses and electives. Students electing this major program also can satisfy the requirements for a certified degree in chemistry as set forth by the American Chemical Society. The combined B.S./M.S. is designed for students whose advanced preparation qualifies them for graduate-level work in their third and fourth years of college.

The major requires a group of prerequisites or their equivalent in advanced placement, a core of courses common to all four degree programs, advanced courses specific to each degree program, and a senior requirement.

Course requirements common to all Chemistry degree programs All degrees require two terms of organic chemistry (CHEM 174 or 220, and CHEM 175, 221, or 230) with laboratory (CHEM 222L and 223L), one term of physical chemistry (CHEM 332 or 328), and one term of inorganic chemistry (CHEM 252).

B.A. degree program The B.A. degree program requires 11 term courses, totaling 10 course credits, beyond the prerequisites. In addition to the common degree requirements and one-term senior requirement, the B.A. degree requires four additional course credits of advanced chemistry lecture or laboratory courses. At least one of the advanced courses must be a lecture course in the Chemistry department and at least one must be a Chemistry laboratory course. CHEM 333 may be counted toward the advanced-course requirement, although not as the sole lecture course.

B.S. degree program The B.S. degree program requires 14 term courses, totaling 13 course credits, beyond the prerequisites. In addition to the common degree requirements and two-term senior requirement, the B.S. degree requires completion of a second term of physical chemistry (CHEM 333), one term of physical chemistry laboratory (CHEM 330L), and four additional course credits of advanced chemistry lecture or laboratory courses. At least one of the advanced courses must be a lecture course in the Chemistry department and at least one must be a Chemistry laboratory course.

B.S. degree program, intensive major The B.S. degree program, intensive major requires 16 term courses, totaling 15 course credits, beyond the prerequisites. In addition to the common degree requirements and two-term senior requirement, the B.S. degree with an intensive major requires completion of a second term of introductory physics numbered 171 or higher, a second term of physical chemistry (CHEM 333), one term of physical chemistry laboratory (CHEM 330L), and five additional course credits of advanced chemistry lecture or laboratory courses. At least two of the advanced courses must be lecture courses in the Chemistry department and at least one must be a Chemistry laboratory course.

Combined B.S./M.S. degree Exceptionally well-prepared students may complete a course of study leading to the simultaneous award of the B.S. and M.S. degrees after eight terms of enrollment. Formal application for admission to this program must be made no later than the last day of classes in the fifth term of enrollment. To be considered for admission, by the end of their fifth term applicants must have achieved at least two-thirds A or A– grades in all of their course credits as well as in all of the course credits directly relating to the major, including prerequisites. Two terms of CHEM 490 must be taken in the fifth and sixth terms with earned grades of A or A– to continue in the program. The B.S./M.S. degree program requires completion of the intensive major requirements, including the senior requirement,
which is typically completed in the fifth and sixth terms. The introductory physics requirement must be fulfilled with PHYS 200, 201 or 260, 261; a term course in physics numbered 400 or higher and approved by the Chemistry DUS may be substituted for the introductory sequence. In addition, eight graduate courses in chemistry (four of which count toward the B.S.) are required. Four terms of research are required, including two terms of research taken in CHEM 490. Students in the program must earn grades of A in at least two of their graduate-level term courses (or in one yearlong course) and have at least a B average in other graduate-level courses. B.S./M.S. candidates also are expected to continue their independent research in a summer internship between their junior and senior years. At the end of their eighth semester students are required to write a thesis summarizing their research activities. The thesis must be written under the guidance of the faculty member who supervises the student’s research and it must be submitted on the final day of classes of the student’s eighth semester to their research adviser. The thesis should be no shorter than 25 pages (double-spaced, twelve-point font, excluding figures, tables, and bibliography) and should normally contain the following sections: Introduction, Results and Discussion, Summary and Conclusions, Research Methods, and Bibliography. Students in the B.S./M.S. program also must present their research in the form of a poster presentation at the end of their sixth semester (to fulfill the requirements of the B.S. degree) and an oral presentation at the end of their eighth semester (to fulfill the requirements of the M.S. degree). Both the poster and oral presentation are coordinated by the instructor of CHEM 490. For more information, see “Simultaneous Award of the Bachelor’s and Master’s Degrees” in section K of the Academic Regulations.

Credit/D/Fail No chemistry courses taken Credit/D/Fail may be counted toward the major (including substitutions for advanced courses).

Roadmap See visual roadmap of the requirements.

SENIOR REQUIREMENT

For the B.A. degree program Students in the B.A. degree program must complete the senior seminar CHEM 400, in which they prepare a capstone essay on a chemistry-related topic. The paper is expected to be fifteen to twenty-five pages in length (double-spaced, twelve-point font, exclusive of figures, tables, and bibliography).

For the B.S. degree program Students in the B.S. degree program may fulfill the senior requirement by completing two terms of the independent research course CHEM 490 and writing a capstone report under the guidance of a faculty member that describes their research activities. Alternatively, they may complete the senior seminar CHEM 400, in which they prepare a capstone essay on a chemistry-related topic, and complete one additional course credit of advanced chemistry lecture or laboratory courses. One term of CHEM 490 may be counted as the additional advanced course. The capstone report or essay is expected to be fifteen to twenty-five pages in length (double-spaced, twelve-point font, exclusive of figures, tables, and bibliography). All students performing research also must present their work in the form of an oral or poster presentation as coordinated by the instructor of CHEM 490.

For the B.S. degree program with an intensive major Students in the B.S. degree program with an intensive major fulfill the senior requirement by completing two terms of the independent research course CHEM 490 and writing a capstone report of fifteen to twenty-five pages (double-spaced, twelve-point font, exclusive of figures, tables, and bibliography) under the guidance of a faculty member that describes their research activities. Students in the intensive major program also must present their work in the form of an oral or poster presentation as coordinated by the instructor of CHEM 490.

ADVISING

Majors are encouraged to begin their programs in the first year to provide the greatest flexibility in scheduling. It is possible, however, to complete the B.S. in as little as six terms if a student has advanced placement. One sample B.S. program follows, but many others are possible:

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<th>First-Year</th>
<th>Sophomore</th>
<th>Junior</th>
<th>Senior</th>
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Substitutions for required courses Up to two terms of advanced science courses outside Chemistry may be counted as electives, with the written approval of the DUS. CHEM 490 may not in any circumstance be substituted for any of the laboratory requirements. The graduate courses CHEM 562L, 564L, and 566L may not be counted toward any requirement of the major.

Programs of study with special emphasis The flexibility of the degree requirements makes it possible for a student’s program of study to emphasize a particular area of specialization in chemistry. For example, a program specializing in chemical biology includes CHEM 421 and two biochemistry electives chosen from MCD 300, MB&B 300, 301, or selected graduate courses. An inorganic chemistry specialization could include CHEM 450, 452, and 457. A program with emphasis in physical chemistry and chemical physics would have three electives chosen from CHEM 430, 440, 442, 470, or a graduate course in quantum mechanics. Students interested in synthetic organic chemistry complete three electives chosen from CHEM 418, 423, 425, or selected graduate courses. An emphasis in biophysical chemistry includes a course in either chemical biology or biochemistry, as well as two electives chosen from graduate courses in biophysics or biochemistry. Students may design programs with other areas of emphasis in consultation with the DUS. For a list of graduate courses appropriate for a particular specialization, consult the DUS.

Approval of major programs of study All Chemistry majors in the sophomore, junior, and senior years must have their programs approved by the DUS. A program tailored to each student’s goals is created and recorded on a Chemistry Course of Study form kept on
file in the department office. Majors who have a current course of study form on file may have their schedules signed by the DUS or by any of the advisers to the major. A current list of advisers to the major may be obtained in the department office.

STUDY ABROAD
In most instances, Chemistry majors find their course of study easier to schedule if they choose to study abroad in a spring term. Students studying abroad in the spring term of their junior year are required to obtain approval for the project that will fulfill their senior requirement before the end of the prior term. For general information on the Year or Term Abroad, see section K of the Academic Regulations.

UNIQUE TO THE MAJOR

Special restrictions on lecture courses Completion of the first term of the general, organic, or physical chemistry sequences CHEM 161 and 165; CHEM 174 or 220 and 175, 221, or 230; and CHEM 332 or CHEM 328 and CHEM 333 with a passing grade is a prerequisite for registration in the subsequent term. Completion of CHEM 163 with a passing grade is a prerequisite for registration in CHEM 167 unless the student’s assigned placement is in CHEM 167.

Students receive credit for only one chemistry sequence of any given type. For example, a student who has completed CHEM 161 and 165 may not subsequently enroll in CHEM 163 or 167; a student who has completed CHEM 174 and 175 may not subsequently enroll in CHEM 220, 221, or 230. Similarly, students may not enroll in a course (typically of lower number) that is a prerequisite to a course they already have taken. Thus, for example, a student who has completed an organic chemistry laboratory cannot subsequently enroll in a general chemistry laboratory.

Special restrictions on laboratory courses Chemistry courses may be taken without the accompanying laboratory, although the department does not recommend it. However, the appropriate lecture course is a prerequisite or corequisite for each laboratory course. This restriction can be waived only by the DUS. Students dropping the lecture course corequisite with a laboratory also must drop the laboratory course.

REQUIREMENTS OF THE MAJOR

Prerequisites CHEM 161 and 165, or 163 and 167; CHEM 134L and 136L (or CHEM 116L, 117L); MATH 115 (MATH 120 or ENAS 151 suggested); PHYS 170, 180, 200, or 260; or equivalents in advanced placement

Number of courses B.A. – at least 11 term courses, totaling 10 course credits, beyond prereqs (incl senior req); B.S. – at least 14 term courses, totaling 13 course credits, beyond prereqs (incl senior req); B.S., intensive major – at least 16 term courses, totaling 15 course credits, beyond prereqs (incl senior req)

Specific courses required All degrees – 2 terms of organic chem (CHEM 174 or 220, and CHEM 175, 221, or 230); 2 terms of organic chem lab (CHEM 222L and 223L); 1 term of physical chem (CHEM 332 or 328); 1 term of inorganic chem (CHEM 252); B.S. – CHEM 330L, 333; B.S., intensive major – CHEM 330L, 333; PHYS 171, 181, 201, or 261

Distribution of courses B.A. and B.S. – 4 addtl course credits in advanced lectures or labs, incl at least 1 lecture and 1 lab; B.S., intensive major – 5 addtl course credits in advanced lectures or labs, incl at least 2 lectures and 1 lab

Substitution permitted Up to 2 relevant advanced science courses in other depts for advanced chem courses with DUS permission

Senior requirement B.A. – CHEM 400; B.S. – 2 terms of CHEM 490, or CHEM 400 and 1 addtl course credit in advanced lecture or lab; B.S., intensive major – 2 terms of CHEM 490

FACULTY OF THE DEPARTMENT OF CHEMISTRY

Professors †Sidney Altman, Victor Batista, Gary Brudvig, Robert Crabtree, †Craig Crews, R. James Cross, Jr. (Emeritus), Jonathan Ellman, John Faller (Emeritus), †Gary Haller, Sharon Hammes-Schiffer, Nilay Hazari, Seth Herzon, Patrick Holland, †Francesco Iachello, Mark Johnson, William Jorgensen, J. Patrick Loria, James Mayer, J. Michael McBride (Emeritus), Scott Miller, Peter Moore (Emeritus), †Anna Pyle, †Lynne Regan, †James Rothman, Martin Saunders, Alanna Schepartz, Charles Schmuttenmaer, †Dieter Söll, David Spiegel, †Thomas Steitz, †Scott Strobel, John Tully (Emeritus), Patrick Vaccaro, Kenneth Wiberg (Emeritus), Elsa Yan, Frederick Ziegler (Emeritus), Kurt Zilm

Associate Professors Jason Crawford, Timothy Newhouse

Assistant Professors Ziad Ganim, †Stavroula Hatziou, Sarah Slavoff, Hailiang Wang

Lecturers Paul Anastas, Christine DiMeglio, N. Ganapathi, Mioy Huynh, Jenny Martinez, Jonathan Parr

†A joint appointment with primary affiliation in another department.
Courses

For Nonmajors without Prerequisites

[ CHEM 101, Chemistry in the Modern World ]

CHEM 104b, Chemistry of Food and Cooking  Elsa Yan
Fundamental principles for understanding chemical structures and interactions as well as energy and speed of chemical processes. Application of these principles to food and cooking, including demonstrations. This course is designed for non-STEM majors. Prerequisite: preference given to students who have not taken AP or college-level chemistry.  SC

Introductory Courses

First-year students planning to take an introductory Chemistry course during their first term are required to preregister over the summer. Those planning to elect CHEM 174, 220, or 332 also must register in person by taking a placement examination as described in the Chemistry department program description and on the Chemistry website. Placement in other introductory Chemistry courses is made on the basis of test scores and other admissions data, as discussed in the Chemistry department program description. The time and place for the orientation meeting, registration, and placement examination are listed in the Calendar for the Opening Days of College. For further information on placement see the Chemistry website.

[ CHEM 119L, Laboratory for Quantitative Foundations of General Chemistry ]

CHEM 134La, General Chemistry Laboratory I  Narasimhan Ganapathi
An introduction to basic chemistry laboratory methods. Techniques required for quantitative analysis of thermodynamic processes and the properties of gases. To accompany or follow CHEM 161 or 163. May not be taken after a higher-numbered laboratory course.  SC  RP ½ Course cr

CHEM 136La or b, General Chemistry Laboratory II  Narasimhan Ganapathi
Introduction to rate and equilibrium measurements, acid-base chemistry, synthesis of inorganic compounds, and qualitative/quantitative analysis. 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.  SC  RP ½ Course cr

* CHEM 161a, General Chemistry I  Patrick Holland
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. Attendance at a weekly discussion section required. Normally accompanied by CHEM 134L. Enrollment by placement only.  QR, SC  RP

* CHEM 163a, Comprehensive University Chemistry I  James Mayer
An in-depth examination of the principles of atomic, molecular, and solid 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. Attendance at a weekly discussion section required. Normally accompanied by CHEM 134L. Enrollment by placement only.  QR, SC  RP

* CHEM 165b, Comprehensive University Chemistry II  Jonathan Parr
Topics include kinetics, chemical equilibrium, acid-base chemistry, free energy and entropy, electrochemistry, and nuclear chemistry. Attendance at a weekly discussion section required. Prerequisite: CHEM 161. Normally accompanied by CHEM 136L. Enrollment by placement only.  QR, SC  RP

* CHEM 167b, Comprehensive University Chemistry II  Hailiang Wang
Topics include kinetics, chemical equilibrium, acid-base chemistry, free energy and entropy, electrochemistry, and nuclear chemistry. Attendance at a weekly discussion section required. Prerequisite: CHEM 163, or with equivalent placement. Normally accompanied by CHEM 156L. Enrollment by placement only.  QR, SC  RP

* CHEM 174a, Organic Chemistry for First-Year Students I  Scott Miller
An introductory course focused on current theories of structure and mechanism in organic chemistry, their development, and their basis in experimental observation. Open to freshmen with excellent preparation in chemistry, mathematics, and physics who have taken the department’s advanced chemistry placement examination. Attendance at a weekly discussion section required. Normally accompanied by CHEM 222L. Enrollment by placement only.  SC  RP

* CHEM 175b, Organic Chemistry for First Year Students II  Jonathan Ellman and Scott Miller
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. After CHEM 174. Normally accompanied by CHEM 223L. Enrollment by placement only.  SC  RP
Intermediate Courses

* CHEM 220a or b, Organic Chemistry
  Staff
  An introductory course covering the fundamental principles of organic chemistry. The laboratory for this course is CHEM 222L. 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. Usually followed by CHEM 221 or 230. SC RP

CHEM 221a or b, The Organic Chemistry of Life Processes
  Staff
  The principles of organic reactivity and how they form the basis for biological processes. The laboratory for this course is CHEM 223L. 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. SC RP

CHEM 222La or b, Laboratory for Organic Chemistry I
  Christine DiMeglio
  First term of an introductory laboratory sequence covering basic synthetic and analytic techniques in organic chemistry. Prerequisite: CHEM 136L or equivalent. After or concurrently with CHEM 174 or 220. SC ½ Course cr

CHEM 222Lb or b, Laboratory for Organic Chemistry II
  Christine DiMeglio
  Second term of an introductory laboratory sequence covering basic synthetic and analytic techniques in organic chemistry. Prerequisite: CHEM 222L. After or concurrently with CHEM 175, 221, or 230. SC ½ Course cr

* CHEM 226La, Intensive Advanced Chemistry Laboratory
  Jonathan Parr
  An intensive course in advanced chemistry laboratory technique intended to bring the student closer to independent research. Included are an independent laboratory project and presentation, introduction to library research, and training in the use of various analytical techniques. Offered subject to available laboratory space and sufficient enrollment. After CHEM 223L. Enrollment is limited; e-mail course instructor for enrollment procedure. WR, SC RP

[ CHEM 230, Organic Chemistry of Biological Pathways ]

CHEM 231Lb, Inorganic Chemistry Laboratory
  Jonathan Parr
  Introductory laboratory course covering synthetic and physical characterization techniques in inorganic chemistry. Prerequisite: CHEM 119L or 222L; concurrently with or after CHEM 232. SC

CHEM 252b, Introductory Inorganic Chemistry
  Robert Crabtree
  Principles and applications of modern inorganic chemistry. Introduction to some of the fundamental concepts of solid-state chemistry, coordination chemistry, bioinorganic chemistry, and organometallic chemistry. Prerequisite: college-level general chemistry. After or concurrently with CHEM 220 or by permission of instructor. May not be taken after CHEM 450, 452, or 457. SC RP

CHEM 238a, Physical Chemistry with Applications in the Biological Sciences
  Ziad Ganim
  Physical chemical principles and their application to the chemical and life sciences. Thermodynamics, chemical and biochemical kinetics, solution physical chemistry, electrochemistry, and membrane equilibria. CHEM 332 is preferred for Chemistry majors. Prerequisites: introductory physics, college-level general chemistry, and single-variable calculus, or permission of instructor; MATH 120 or ENAS 151 suggested. May not be taken after CHEM 332. QR, SC RP

CHEM 330La, Laboratory for Physical Chemistry I
  Patrick Vaccaro
  Introduction to the tools and techniques of modern experimental physical chemistry, including analog/digital electronics, quantitative measurements of basic thermodynamic properties, and nuclear magnetic resonance spectrometry. After or concurrently with CHEM 328 or 332. Meets on Wednesday, Thursday, and Friday from 1:30 to 2:20 for the first week of the term. SC RP

[ CHEM 331L, Laboratory for Physical Chemistry II ]

* CHEM 332a, Physical Chemistry with Applications in the Physical Sciences I
  Charles Schmuttenmaer
  A comprehensive survey of modern physical and theoretical chemistry, including topics drawn from thermodynamics, chemical equilibrium, electrochemistry, and kinetics. Prerequisites: introductory physics, college-level general chemistry, and single-variable calculus, or permission of instructor; MATH 120 or ENAS 151 suggested. May not be taken after CHEM 328. QR, SC RP

* CHEM 332b, Physical Chemistry with Applications in the Physical Sciences II
  Patrick Vaccaro
  Continuation of CHEM 332, including topics drawn from quantum mechanics, atomic/molecular structure, spectroscopy, and statistical thermodynamics. Prerequisite: CHEM 328 or 332, or permission of instructor. Recommended preparation: familiarity with differential equations. QR, SC RP

* CHEM 335Lb, Materials and Biophysical Chemistry Laboratory
  Ziad Ganim and Jonathan Parr
  A laboratory course covering physical methods and chemical synthesis in materials and biophysical chemistry. Techniques include solution phase synthesis, solid state synthesis, UV-Vis, fluorescence, optical microscopy, SEM, STM, single molecule fluorescence, and optical trapping methods. After two terms of general chemistry with laboratory, or concurrently with CHEM 333. SC

Advanced Courses

* CHEM 400a, Current Chemistry Seminar
  Jonathan Parr
  Designed to engage students in the Chemistry research-seminar program by providing requisite scientific guidance and a forum for directed discussion. Participants explore current avenues of chemical research as presented orally by the prime movers in the field, thereby
exploring the frontiers of current knowledge while still retaining the structured environment of a classroom. May fulfill all or part of the senior requirement for the Chemistry major, as detailed in the program description in the YCPS.

* **CHEM 418a, Advanced Organic Chemistry I**  William Jorgensen  
Concise overview of structure, properties, thermodynamics, kinetics, reactions, and intermolecular interactions for organic molecular systems. Prerequisites: two terms of organic chemistry, CHEM 328 or 332, and CHEM 333.  SC  RP

**CHEM 421a, Chemical Biology**  Sarah Slavoff  
A one-term introduction to the origins and emerging frontiers of chemical biology. Discussion of the key molecular building blocks of biological systems and the history of macromolecular research in chemistry. Prerequisites: two terms of organic chemistry, and BIOL 101 or equivalent; BIOL 102 recommended.  SC

[ **CHEM 423, Synthetic Methods in Organic Chemistry** ]

**CHEM 425b, Spectroscopic Methods of Structure Determination**  Martin Saunders  
Applications of NMR, ESR, infrared, UV, visible, and mass spectroscopy to chemical problems concerning structures and reactions. X-ray crystallography. Computer simulation of NMR spectra. Prerequisites: two terms of organic chemistry and CHEM 333.  SC  RP

**CHEM 426b, Computational Chemistry and Biochemistry**  Sharon Hammes-Schiffer and William Jorgensen  
An introduction to modern computational methods employed for the study of chemistry and biochemistry, including molecular mechanics, quantum mechanics, statistical mechanics, and molecular dynamics. Special emphasis on the hands-on use of computational packages for current applications ranging from organic reactions to protein-ligand binding and dynamics. After organic chemistry and physical chemistry.  QR, SC  RP

**CHEM 430a, Statistical Mechanics and Thermodynamics**  Victor Batista  
The fundamentals of statistical mechanics developed and used to elucidate gas phase and condensed phase behavior, as well as to establish a microscopic derivation of the postulates of thermodynamics. Topics include ensembles; Fermi, Bose, and Boltzmann statistics; density matrices; mean field theories; phase transitions; chemical reaction dynamics; time-correlation functions; and Monte Carlo and molecular dynamics simulations. Prerequisites: CHEM 328 or 332, and CHEM 333, or permission of instructor.  QR, SC  RP

**CHEM 437a, Chemistry of Isotopes**  Martin Saunders  
Advanced applications of isotopes to chemical problems and the theory associated with them, including kinetic and equilibrium isotope effects, tracer applications, and dating.  RP

**CHEM 440a, Molecules and Radiation I**  Kurt Zilm  
An integrated treatment of quantum mechanics and modern spectroscopy. Basic wave and matrix mechanics, perturbation theory, angular momentum, group theory, time-dependent quantum mechanics, selection rules, coherent evolution in two-level systems, line shapes, Bloch equations, and NMR spectroscopy. Prerequisite: CHEM 333 or permission of instructor.  QR, SC  RP

**CHEM 442b, Molecules and Radiation II**  Mark Johnson  
An extension of the material covered in CHEM 440 to atomic and molecular spectroscopy, including rotational, vibrational, and electronic spectroscopy, as well as an introduction to laser spectroscopy. Prerequisite: CHEM 440 or permission of instructor.  QR, SC  RP

**CHEM 450b, Physical Methods in Inorganic Chemistry**  Patrick Holland  
Elementary group theory, molecular orbitals, states arising from molecular orbitals containing several electrons, ligand field theory, and electronic structure of metal complexes. Introduction to physical methods used in the determination of molecular structure and the bonding of polyatomic molecules. May be taken independently of CHEM 452. Prerequisites: CHEM 328 or 332 and CHEM 333; CHEM 457 or equivalent.  SC  RP

**CHEM 452a, Advanced Organic Chemistry I**  Robert Crabtree  
A survey of the organometallic chemistry of the transition elements and of homogeneous catalysis. May be taken independently of CHEM 450. Prerequisites: two terms of organic chemistry and CHEM 252.  SC  RP

**CHEM 457a, Modern Coordination Chemistry**  Nilay Hazari  
The principles of modern inorganic chemistry. Main group and transition element chemistry: reactions, bonding, structure, and spectra. Prerequisite: CHEM 252 or permission of instructor.  SC  RP

**CHEM 470a, Quantum Chemistry**  Sharon Hammes-Schiffer  
The elements of quantum mechanics developed and illustrated with applications in chemistry and chemical physics. Prerequisites: CHEM 333, and MATH 120 or ENAS 151.  QR, SC  RP

**CHEM 480a or b, Introduction to Independent Research in Chemistry**  Staff  
After consultation with the DUS, students engage individual experimental and/or theoretical research problems in the laboratories of a selected faculty member within the Chemistry department. At the end of the term, students submit a brief report summarizing goals, methods, and accomplishments. For each term of enrollment, students must complete the CHEM 480 registration form, available in the DUS office, and have it signed by their faculty research mentor. It must be submitted to the Chemistry DUS for final approval no later than the last week of classes in the immediately preceding academic term. Individuals wishing to perform independent research must have demonstrated proficiency in the aspects of chemistry required for the planned project, as ascertained by the supervising faculty member, and must meet basic safety requirements prior to undertaking any activities, including certified completion of the online courses entitled Laboratory Chemical Training and Hazardous Chemical Waste Training administered by the Office of Environmental Health and
Safety (EHS) at http://ehs.yale.edu/training. At least ten hours per week of research are required (including time spent on requisite safety training), with the faculty mentor affirming this level of student commitment by midterm. This course may be taken multiple times for Pass/Fail credit, subject to restrictions imposed by Yale College.  

* CHEM 490a or b, Independent Research in Chemistry  
Jonathan Parr
Senior Chemistry majors engage individual experimental and/or theoretical research problems in the laboratories of a selected faculty member in the Chemistry department or in a closely related field of molecular science. CHEM 490 registration forms, found in the DUS office, must be signed by the student’s faculty research mentor and submitted it to the Chemistry DUS for final approval no later than the last week of classes in the immediately preceding academic term. Mandatory class meetings address issues of essential laboratory safety and ethics in science, with other class sessions focusing on core topics of broad interest to Chemistry students, including online literary research, oral presentation skills, and effective scientific writing. At least ten hours of research are required per week. Students are assigned letter grades, subject to restrictions imposed by Yale College. In special cases and with DUS approval, juniors may take this course.  

GRADUATE COURSES OF INTEREST TO UNDERGRADUATES
Graduate courses in chemistry that may be of particular interest to undergraduates are listed in the online bulletin of the Graduate School. Information about them is available in the office of the director of undergraduate studies. Enrollment requires permission of both the director of graduate studies and the instructor, with pre-approval by the director of undergraduate studies if credit towards the requirements of the major is being sought.