# Information for Graduate Students

The Institute offers graduate work leading to the degrees of Master of Science and Doctor of Philosophy. In addition, it offers the following intermediate degrees: Aerospace Engineer, Civil Engineer, Electrical Engineer, and Mechanical Engineer.

The academic work of the Institute is organized into six divisions: Biology; Chemistry and Chemical Engineering; Engineering and Applied Science; Geological and Planetary Sciences; the Humanities and Social Sciences; and Physics, Mathematics and Astronomy.

Graduate work at the Institute is further organized into graduate options, which are supervised by those professors whose interests and research are closely related to the area of the option, within the administrative jurisdiction of one or more of the divisions. The graduate student working for an advanced degree in one of the graduate options is associated with an informal group of those professors who govern the option, other faculty including research associates and fellows, and other graduate students working for similar degrees.

A faculty member serves as the representative for an option. The option representative provides consultation on academic programs, degree requirements, financial aid, etc., and provides general supervision to graduate students in the option. The Committee on Graduate Studies, which includes the option representatives, elected members of the faculty at large, and graduate students appointed by the Graduate Student Council, exercises supervision over the scholastic requirements established by the faculty for all advanced degrees, provides policy guidance to the dean of graduate studies, and certifies all candidates for graduate degrees to the faculty for their approval. The option representatives for 2010–11 are as follows:



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| Aerospace | Prof. D. Meiron |
| Applied and Computational Mathematics | Prof. H. Owadi |
| Applied Mechanics | Profs. N. Lapusta and T. Heaton |
| Applied Physics | Prof. S. Troian |
| Astrophysics | Prof. C. Hirata |
| Behavioral and Social Neuroscience | Prof. R. Kiewiet |
| Biochemistry and Molecular Biophysics | Prof. R. Phillips |
| Bioengineering | Prof. N. Pierce |
| Biology | Prof. B. Hay |
| Chemical Engineering | Prof. K. Giapis |
| Chemistry | Prof. P. Dervan |
| Civil Engineering | Prof. T. Heaton |
| Computation and Neural Systems | Prof. S. Shimojo |
| Computer Science | Prof. C. Umans |
| Control and Dynamical Systems | Prof. R. Murray |
| Electrical Engineering | Prof. A. Hajimiri |
| Environmental Science and Engineering | Prof. P. Wennberg |

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| Geological and Planetary Sciences | Prof. D. Stevenson |
| Materials Science | Prof. B. Fultz |
| Mathematics | Prof. A. Kechris |
| Mechanical Engineering | Prof. N. Lapusta |
| Physics | Prof. F. Porter |
| Social Science | Prof. R. Kiewiet |

## GRADUATE POLICIES AND PROCEDURES

### Admission to Graduate Standing

*Application*
An application for admission can be completed electronically at http://www.gradoffice.caltech.edu. Admission will be granted *only to a limited number of students of superior ability*, and application should be made as early as possible. In general, admission to graduate standing is effective for enrollment only at the beginning of the next academic year. The California Institute of Technology encourages applications from members of groups underrepresented in science and engineering, including women. Applicants will automatically be considered for financial aid; no additional application is required. Completed applications are due in the Graduate Office between December 15 and January 15. Please refer to http://www.gradoffice.caltech.edu for specific deadlines. Some options will review an application received after the deadline, but that applicant may be at a disadvantage in the allocation of financial assistance or in the priority for admission.



To be admitted to graduate standing, an applicant must in general have received a bachelor's degree representing the completion of an undergraduate course in science or engineering equivalent to one of the options offered by the Institute. He or she must, moreover, have attained such a scholastic record and present such recommendations as to indicate fitness to pursue, with distinction, advanced study and research. Admission sometimes may have to be refused solely on the basis of limited facilities in the option concerned.

*Required Tests*
The verbal, quantitative, and analytical components of the Graduate Record Examination are required by all graduate options, and subject scores are required by most options as part of the application for graduate admission.

*International Students*
In order to be admitted for graduate study, students from non-English-speaking countries are expected to read, write, and speak English and comprehend the spoken language. Although not *required* for admission, it is important to demonstrate a strong capability in English prior to admission to Caltech, as it is one of

the criteria for admission and financial aid. In addition, to be a candidate for an advanced degree, the student must have acquired the power of clear and forceful self-expression in both oral and written English.

Applicants whose first or native language is not English are required to take a test of English proficiency as part of the application procedure. These tests are given at centers throughout the world, on several dates each year. Caltech recognizes scores from the Educational Testing Service (ETS), Pearson Test of English Academic (PTE Academic), and from the Cambridge Examinations and the International English Language Testing System (IELTS). In addition, applicants who are taking the TOEFL exam are highly encouraged to take the Test of Written English (TWE) and the Test of Spoken English (TSE) and submit these scores as part of their application. Applicants should arrange for the results of these tests to be sent to the Office of the Dean of Graduate Studies (Graduate Office) prior to the application deadline (institutional code 4034).

The testing schedules for and information on the TOEFL, TWE, and TSE may be obtained by writing to TOEFL, Educational Testing Service, Princeton, NJ 08540. They are also available online at http://www.toefl.org.

The testing schedules for and information on the IELTS exam may be obtained by writing to The British Council, Bridgewater House, 58 Whitworth Street, Manchester M1 6BB, United Kingdom. They are also available online at http://www.ielts.org.

It is strongly recommended that students who do not achieve a high score on these tests, or who have little opportunity to communicate in English, make arrangements for intensive work during the summer preceding their registration. All international students are tested upon arrival at Caltech and, if found to be seriously deficient in their ability to communicate in English, must take special courses in English as a Second Language (ESL).



## Visiting Student Appointments

Visiting student forms may be obtained from the Graduate Office and must, before submission to the dean of graduate studies, include appropriate documentation and carry the recommendation of the option representative and the Caltech faculty host. Visiting students are categorized into two main classifications.

*Special Students*

Students who hold a bachelor's degree or the equivalent may, in exceptional cases, be admitted as special graduate students to carry out full-time studies at the Institute. This status is ordinarily restricted to students who are registered in, or are on sabbatical from, an advanced degree program at another institution and who need to make use of resources available at Caltech. Admission requires sponsorship by a Caltech faculty member, and application should be

made directly to the dean of graduate studies, following the visiting student instructions that may be obtained from the Graduate Office. Special students will not be considered to be working toward a Caltech degree, and courses taken under this program cannot be used to fulfill the requirements for a Caltech degree. Registration as a special student does not count toward the minimum residency requirement for an advanced degree.

Special students must be registered for a minimum of 36 units each term and may enroll in research and/or courses, which may be transferred to their home institution. Special students are eligible for Caltech benefits as defined by their enrollment status, and those students who receive a salary will be billed for tuition and tuition remission will be deducted from the supporting grant. Special students who do not receive a Caltech salary will be billed the minimum tuition rate. (For current rates, see the expense summary on page 255.)

*Visiting Student Researchers*

In exceptional cases, students from other universities may visit Caltech to carry out research under the direction of a Caltech faculty member. This status is ordinarily restricted to those students who will not be enrolled at Caltech and are registered in, or are on sabbatical from, an advanced degree program at another institution and who need to make use of resources available at Caltech. Admission requires sponsorship by a Caltech faculty member, and application should be made directly to the dean of graduate studies, following the visiting student instructions that may be obtained from the Graduate Office. Visiting student researchers will not receive academic credit from Caltech, are not eligible to receive a salary through the Institute payroll, and are not eligible for Caltech benefits. Visiting student researchers are required to provide proof of insurance for the duration of the visit, and they may be reimbursed for research-related expenses, but it is the Caltech faculty member's responsibility to ensure that the supporting grant can be used for such purposes and that there are no restrictions on spending. Visiting student researchers are required to check in with the Registrar's Office upon arrival to obtain a Caltech identification card. (Students receiving a salary and requiring academic credit should be appointed as special students; see the special students section on page 239.)



*Exchange Programs*

Some academic options have formal exchange programs that they have arranged with other institutions. Exchange students must have a visiting student appointment, and the type of appointment will depend on the agreement negotiated for the particular exchange program. These programs are administered by the option, and application should be made directly to the dean of graduate studies by completing a special form provided for this purpose that may be obtained from the Graduate Office.

## Graduate Residence

One term of residence shall consist of one term's work of not fewer than 36 units of advanced work in which a passing grade is recorded. Advanced work is defined as study or research in courses whose designated course number is 100 or above. If fewer than 36 units are successfully carried, the residence will be regarded as short by the same ratio, but the completion of a greater number of units in any one term will not be regarded as increasing the residence. In general, the residency requirements are as follows: for Master of Science, a minimum of three terms (one academic year) of graduate work; for Aerospace Engineer, Civil Engineer, Electrical Engineer, and Mechanical Engineer, a minimum of six terms (two academic years) of graduate work; and for Doctor of Philosophy, a minimum of nine terms (three academic years) of graduate work.

## Registration

Graduate students are required to register for each term of residence, whether they are attending a regular course of study, carrying on research, doing independent reading, writing a thesis, or utilizing any other academic service or campus facility.

A graduate student must be registered for 36 or more units to be classified as a full-time student, but course loads greater than 45 units are more common. A graduate student who registers for less than 36 units, or who undertakes activities related to the Institute aggregating more than 62 hours per week (in class, research, and teaching assistantship units), must receive approval from the dean of graduate studies. Petition forms for this purpose may be obtained from the Graduate Office's website and must carry the recommendation of the option representative of the student's major option before submission to the dean of graduate studies.



Graduate students register during a two-week period each quarter. A late registration fee of $50 is assessed for failure to register on time. Graduate students with a bursar's bill balance of $1,500 or more will have a hold placed on their registration for the subsequent term the day before online registration opens. The hold will be released once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.

Before registering, students should consult with members of the option in which they are taking their major work to determine the studies that they can pursue to the best advantage. An adviser is assigned to each entering graduate student by the option representative. In most options, a new adviser is assigned when the student begins research. Only members of the professorial faculty may serve as advisers. With the approval of the dean of graduate studies, any graduate student whose work is not satisfactory may be refused registration at the beginning of any term by the division in which the student is doing his or her major work.

In registering for research, students should indicate the name of the instructor in charge, and should consult with him or her to determine the number of units to which the proposed work corresponds. At the end of the term, the instructor in charge may decrease the number of units for which credit is given if he or she feels that the progress of the research does not justify the full number originally registered for.

Students will not receive credit for courses unless they are properly registered. The students themselves are charged with the responsibility of making certain that all grades to which they are entitled have been recorded.

All changes in registration must be reported, on drop or add cards, to the Registrar's Office by the student. Such changes are governed by the last dates for adding or dropping courses as shown on the academic calendar on pages 4 and 5. A student may not withdraw from or add a course after the last date for dropping or adding courses without his or her option's consent and the approval of the dean of graduate studies.

If the withdrawal occurs after Add Day of any term, a W (standing for "withdrawn") will be recorded on the student's transcript for all courses in which the student is enrolled. A grade of W is not included in the computation of the student's grade-point average.

*Academic Year and Summer Registration*

Most courses are taught during the three 12-week quarters that make up the academic year. However, predoctoral students are strongly encouraged to continue their research throughout the summer quarter. They are entitled to at least two weeks' annual vacation (in addition to Institute holidays), but they should arrange their vacation schedules with their research advisers early in each academic year. Any questions should be referred to the dean of graduate studies.



All students in residence must be registered. There is no tuition charge for summer research units. To maintain full-time student status, 36 units must be taken in the summer quarter.

*Sabbatical*

Graduate students are required to maintain their admission status until all requirements for a degree are fulfilled, whether by continuity of registration or on the basis of an approved sabbatical. A sabbatical for medical or other reasons may be approved for up to one year at a time. A sabbatical will be approved to meet military obligations, and tuition adjustments will be made if the sabbatical must be initiated within a term (see pages 147–150). An approved sabbatical indicates that the student can return to the option at the end of the sabbatical. A sabbatical for medical reasons requires a petition to the dean of graduate studies, supported by a physician, prior to reinstatement. Financial aid awarded by the Institute will

not be deferred from the term for which it was originally offered and must be requested again for the term of reenrollment.

In general, international students cannot take a sabbatical without jeopardizing their visa status. Students who hold nonimmigrant visas must meet with an adviser in the International Student Programs Office to determine the impact that a sabbatical will have on their immigration status.

Detached duty status continues registration for a student doing research at another location, such as a national facility, for an extended period. Reduced duty status continues registration for a student who cannot carry a full load due to medical disability, including pregnancy.

Graduate students who become pregnant during their studies must be provided a minimum of six weeks of paid leave with full benefits and another six weeks of family bonding leave without pay but maintaining full benefits. Family bonding leave without pay is available to the father, if the father is a graduate student at Caltech. The paid and unpaid leaves are intended to cover normal pregnancy and childbirth. If a longer leave is required due to medical complications, a six-month extension of leave beyond the 12 weeks may be taken as a medical leave with approval of the dean of graduate studies.

Petition forms for an approved sabbatical, or detached or reduced duty status, may be obtained from the Graduate Office's website and must, before submission to the dean of graduate studies, carry the recommendations of the student's option representative and, where appropriate, the thesis adviser. In case of a lapse in admission status, readmission must be sought before academic work may be resumed or requirements for the degree completed. Registration is required for the quarter in which the thesis defense is undertaken, with the exception of the first week of each quarter, but is not normally allowed beyond the last date of the quarter. Approval of the dean of graduate studies is required for any student seeking to enroll for subsequent terms following the thesis defense.



The dean of graduate studies may place a graduate student on involuntary sabbatical if persuaded by the evidence that such an action is necessary for the protection of the Institute community or for the personal safety or welfare of the student involved. Such a decision by the dean is subject to automatic review within seven days by the vice president for student affairs.

## Guidelines for Graduate Student Advising

The relationship between a faculty adviser and graduate student should be founded on mutual respect and open communication. Advisers and students should discuss the nature of their working relationship early and continue this discussion throughout their period of collaboration to ensure mutually understood and com-

patible expectations. These discussions should be frequent and open, and should include not only work, research goals, and performance reviews, but also change of status, time for personal and family responsibilities, time off, and concerns about academic or work situations. Both the student and adviser have the obligation to initiate meetings as necessary to ensure the success of the relationship.

After achieving candidacy, each Ph.D. student should be assigned a thesis advising committee of three or more faculty members. This committee should meet informally at least once a year beginning in the fourth year of graduate study.

The graduate student–faculty adviser relationship should be guided by norms of fairness and professionalism. Both faculty and graduate students should avoid relationships that conflict with their respective roles and duties at Caltech. Both are bound by the prevailing policies prohibiting discrimination and harassment (pages 61–62 and 68–77). Concerns relating to academic or work situations should be raised promptly between the persons directly involved, and handled informally if possible. Both students and advisers have the responsibility to raise and address concerns and conflicts promptly, honestly, and in a manner that conforms with academic integrity and professionalism. Caltech policy requires that students' concerns be addressed fairly and promptly, and prohibits retaliation or discrimination against students for appropriately voicing or raising a concern.

If a problem remains unresolved or if direct discussion is not possible, a student can seek assistance from division officers (e.g., option representatives), the graduate deans, or the assistant vice president for student affairs. At any time, a student may request that discussions remain confidential. For more details about sources of assistance, consult the graduate option regulations (pages 264–339) and the Student Grievance Procedure (page 49).



## Part-Time Programs

Part-time graduate study programs at the Institute are for graduate students who cannot devote full time to their studies and are allowed to register only under special arrangements with a sponsoring organization, and such students are subject to the following rules:

*Degree Programs*

- Applicants for the part-time program must submit a regular application form accompanied by a detailed plan for meeting the course requirements for the degree.
- Any research work done for academic credit shall be supervised by a Caltech faculty member.
- In general, students admitted to the part-time program are required to take at least 27 units of graduate course work or research work each term during the first academic year.

- Any option at the Institute retains the right to not participate in the program or to accept it under more stringent conditions.

*Nondegree Programs*

Caltech employees, both campus and JPL, are eligible to apply to take one or more graduate courses for credit. Participants in this program will not be considered to be working toward a Caltech degree, in contrast to the part-time program for graduate degrees described above, and courses taken under this program cannot be used to fulfill the requirements for a Caltech degree.

At least one month prior to the start of the term, the employee should have an initial discussion with the option representative of the option in which the course is to be taken. Application should be made to the Graduate Office by completing the special form provided for this purpose, and providing a transcript of academic work and one letter of recommendation. The employee must meet the prerequisites for the course, and must obtain the written permission of the instructor. Individual options may require further information such as GRE scores. The decision on admission to take each course will be made by the course instructor and the option representative, with final approval by the dean of graduate studies. Taking an additional course at a later time will require full reapplication. It is the employee's responsibility to arrange a revised work schedule with the appropriate supervisor. Approval of the employee's supervisor is required.

Part-time nondegree students are subject to the Honor System (see page 32) and are under the purview of the dean of graduate studies. They may take only courses numbered 100 or higher. Research courses are excluded from the program. For courses in which a letter grade is offered, these students may not register to receive a pass/fail grade in the course, nor can credit for the course be obtained by examination. The option may limit the number of nondegree students admitted to any one course.



## Working at Special Laboratories

- Students who desire to take advantage of the unique opportunities available at one of the special laboratories (e.g., JPL) for Ph.D. thesis work may be allowed to do so, provided that they maintain good contact with academic life on campus, and the laboratory involved commits support for the duration of the thesis research, and provided that all Caltech graduate thesis research carried out at a special laboratory is under the supervision of Caltech faculty members.
- A student's request to carry out thesis work at a special laboratory should be formally endorsed by the appropriate committee of his or her option and by the special laboratory, on a petition submitted through the option representative to the dean of graduate studies. The special laboratory should recognize its

commitment of special equipment or any other resources required for the thesis work. Approval by the special laboratory should also indicate that the thesis topic is a sensible one, and that it is not likely to be preempted by the laboratory.

- A student may take similar advantage of unique opportunities at a corporate or governmental research and development facility under the same conditions, providing that there exists a formal written agreement between the R&D facility and the student's thesis adviser, and that advance written approval is obtained from the dean of graduate studies. Such curricular practical training may in some cases involve full-time employment at the laboratory for a limited period of time for the purpose of engaging in the essential data collection that is integral to a student's doctoral dissertation. Typically, such students who are not in a local laboratory are placed on detached duty status.
- Employment by a special laboratory of a graduate student for work not connected with his or her thesis should be regarded as equivalent to other outside employment.

### Exchange Program with Scripps Institution of Oceanography

An exchange program has been established with the Scripps Institution of Oceanography (SIO), University of California, San Diego, permitting Caltech graduate students to enroll in and receive credit for graduate courses offered by SIO. Arrangements should be made through the student's major option and the Graduate Office. The student must obtain the advance approval of the instructors of courses to be taken at SIO. In some cases, when it is in the best interests of the student, arrangements may be made for the student to be temporarily in full-time residence at SIO.



Thesis research done partly at SIO may be arranged directly by the student's option and the staff of appropriate research laboratories at SIO, without the necessity of enrolling for SIO courses designated for research; in this case the student will continue to be under the supervision of his or her Caltech thesis adviser and will enroll for Caltech research units.

## GENERAL REQUIREMENTS FOR GRADUATE DEGREES

### Degree of Master of Science

The Master of Science degree is a professional degree designed to prepare a student for teaching, for further graduate studies, or for more advanced work in industry. Detailed requirements are based primarily on professional studies, and the program should be planned in consultation with the faculty in the appropriate disci-

pline. Under normal circumstances, the requirements for the M.S. degree can be completed in one academic year.

A student who enters the Institute holding a master's degree from another institution will not normally be awarded a master's degree in the same field from the Institute unless the initial admission to Caltech graduate standing indicated that the student was to be a master's candidate. A student may not normally be awarded two master's degrees from the Institute.

Special regulations for the master's degree are listed under each graduate option. Several options do not offer an M.S. degree except in special circumstances.

*Residence and Units of Graduate Work Required.* At least one academic year of residence at the Institute and 135 units of graduate work at the Institute subsequent to the baccalaureate degree are required for the master's degree. Included in these units are at least 27 units of free electives or of required studies in the humanities numbered 100 or above. Courses taken while enrolled as a Caltech undergraduate student in excess of the bachelor's degree requirements may be counted toward the master's degree requirements with the approval of the academic option representative and the dean of graduate studies.

To qualify for a master's degree, a student must complete the work indicated in the section on special regulations for his or her option with a grade-point average for the approved M.S. candidacy courses of at least 1.9.

In special cases, with the approval of the instructor and the dean of graduate studies, courses taken elsewhere before enrollment at the Institute may be offered in place of specifically required courses. An examination may be required to determine the acceptability of such courses. Course credit, if granted, shall not count toward the 135-unit and residency requirements.



*Joint B.S./M.S. Degree.* In exceptional cases, undergraduate students may pursue a joint B.S./M.S. program of study in some options. Several options do not allow a joint B.S./M.S. degree. Students should contact the graduate option representative to find out if the joint B.S./M.S. degree is possible in a particular option. Such students must follow the normal procedures for admission to the M.S. program in the option of their choice. Students attending courses or carrying out research toward an M.S. degree before completion of their B.S. degree requirements will be considered as undergraduate students and will not be eligible for graduate financial aid, graduate housing, or other graduate student privileges.

*Admission to M.S. Candidacy.* Before the midpoint of the first term of the academic year in which the student expects to receive the degree, he or she should file in the Graduate Office an application for admission to candidacy for the degree desired. On the M.S. candidacy form, the student must submit a proposed plan of study, which must have the approval of his or her option representative and, if a thesis is required, of his or her research adviser.

Some options require a thesis or research report in addition to course requirements. The thesis or research report must be signed off on the M.S. candidacy form by the research adviser no later than two weeks before the degree is to be conferred. This approved plan of study will constitute the requirements for the degree. Any modifications must be approved by the option representative, and the initialed plan of study resubmitted to the Graduate Office at least two weeks before commencement.

Students enrolled for the joint B.S./M.S. program must complete a minimum of 486 units for the B.S. program and 135 units for the M.S. program with no overlapping of courses.

## Engineer's Degree

Engineer's degrees are awarded in aerospace, civil engineering, electrical engineering, and mechanical engineering. The work for an engineer's degree must consist of advanced studies and research in the field appropriate to the degree desired. It must conform to the special requirements established for that degree and should be planned in consultation with the members of the faculty concerned. Students who have received the master's degree and wish to pursue further studies leading toward either the engineer's or the doctor's degree must file a new petition to continue graduate work toward the desired degree. Students who have received an engineer's degree will not in general be admitted for the doctor's degree.

*Residence.* At least six terms of graduate residence subsequent to a baccalaureate degree equivalent to that given by the Institute are required for an engineer's degree. Of these, at least the last three terms must be at Caltech. It must be understood that these are minimum requirements, and students must often count on spending a somewhat longer time on graduate work.



To qualify for an engineer's degree, a student must complete the work prescribed by his or her supervising committee with a grade-point average of at least 1.9. Research work and the preparation of a thesis must constitute no fewer than 55 units. More than 55 units may be required by certain options, and the student should determine the particular requirements of his or her option when establishing a program.

*Admission to Candidacy.* Before the midpoint of the first term of the academic year in which the student expects to receive the degree, he or she must file in the Graduate Office an application for admission to candidacy for the degree desired. Upon receipt of this application, the dean of graduate studies, in consultation with the chair of the appropriate division, will appoint a committee of three members of the faculty to supervise the student's work and to certify its satisfactory completion. One of the members of the committee must be in a field outside the student's major field of study. The student should then consult with this committee in planning the details of his or her work. The schedule of work as approved by the com-

mittee shall be entered on the application form and shall then constitute a requirement for the degree. Changes in the schedule will not be recognized unless initialed by the proper authority. No course that appears on the approved schedule and for which the applicant is registered may be removed after the last date for dropping courses, as listed in the *Catalog*.

The student will be admitted to candidacy for the degree when the supervising committee certifies (a) that all the special requirements for the desired degree have been met, with the exception that certain courses of not more than two terms in length may be taken after admission to candidacy; (b) that the thesis research has been satisfactorily started and can be finished at the expected date; (c) that the candidate demonstrates competence in oral and written English.

Students may demonstrate competence in written English by scoring 5 or above on the TWE examination or by having their final thesis accepted by the faculty. To determine oral competence in English, students from non-English-speaking countries are screened during the fall orientation session. Those who do not pass the screening must enroll in ESL 101 during the fall quarter and must subsequently score at least 50 on the standardized NTS (National Testing Service) SPEAK test. Students who score below 50 on the SPEAK test are urged to continue taking ESL classes; they must pass the SPEAK test before admission to candidacy. To help students pass this test, ESL courses are held throughout the school year and intensive English is offered in the summer. The Graduate Office will maintain a record of the test scores and will provide them to the option representatives, as needed, to verify that the student has met this requirement. (Note: Other ESL courses are open to all students who want to improve their oral skills, as described on page 450.)



Admission to candidacy must be obtained by the midpoint of the term in which the degree is to be granted.

*Thesis.* At least two weeks before the degree is to be conferred, each student is required to submit to the dean of graduate studies two copies of his or her thesis in accordance with the regulations that govern the preparation of doctoral dissertations. These regulations may be obtained from the Graduate Office. The candidate must obtain written approval of the thesis by the chair of the division and the members of the supervising committee, on a form obtained from the Graduate Office.

The use of "classified" research as thesis material for any degree will not be permitted. Exceptions to this rule can be made only under special circumstances, and then only when approval is given by the dean of graduate studies before the research is undertaken.

*Examination.* At the discretion of the option in which the degree is desired, a final examination may be required. This examination would be conducted by a committee appointed by the candidate's supervising committee.

## Degree of Doctor of Philosophy

The degree of Doctor of Philosophy is conferred by the Institute primarily in recognition of breadth of scholarship, depth of research, and the power to investigate problems independently and efficiently, rather than for the completion of definite courses of study through a stated period of residence. The work for the degree must consist of research and the preparation of a thesis describing it, and of systematic studies of an advanced character, primarily in science or engineering. In addition, the candidate must have acquired the power of clear and forceful self-expression in both oral and written English.

Subject to the general supervision of the Committee on Graduate Study, the student's work for the degree of Doctor of Philosophy is specifically directed by the division in which he or she has chosen the major subject. Each student should consult his or her division concerning special divisional and option requirements.

*Admission.* With the approval of the dean of graduate studies, students are admitted to graduate standing by the option in which they choose their major work toward the doctor's degree. In some cases, applicants for the doctor's degree may be required to register for the master's or engineer's degree first; however, these degrees are not general prerequisites for the doctor's degree. Students who have received the master's degree and wish to pursue further studies leading toward either the engineer's or the doctor's degree must file a request to continue graduate work toward the desired degree. Students who have received an engineer's degree will not, in general, be admitted for the doctor's degree.



A student who holds a Ph.D. degree from another institution will not normally be admitted to graduate standing at Caltech to pursue a second Ph.D. degree. A student will not normally be awarded two Ph.D. degrees from the Institute.

*Minor Programs of Study.* The Institute does not require a minor for the Ph.D. degree, but the individual options may have minor requirements as part of their requirements for the major.

A student may undertake a minor program of study in most options as specified in this catalog under the section "Special Regulations of Graduate Options." Completion of a minor program of study is recognized on the Ph.D. diploma by the statement "…and by additional studies constituting a minor in [name of option]."

A minor program of study should be at a level of study in the minor substantially beyond that typically acquired by students as part of their major requirements. Most options require 45 units or more, including at least one 200-level course and a coherent program of the supporting 100-level courses. The faculty of the minor option may approve a proposed minor program on the basis of overall class performance and/or by an oral examination. Detailed

requirements for minor options are listed under the individual options. Students cannot use courses required by their major option in fulfillment of the minor requirement.

*Residence.* At least nine terms (three academic years) of residence subsequent to a baccalaureate degree equivalent to that given by the Institute are required for the doctor's degree. Of this, at least one year must be in residence at the Institute. It should be understood that these are minimum requirements, and students must usually count on spending a somewhat longer time in residence. A student whose undergraduate work has been insufficient in amount or too narrowly specialized, or whose preparation in his or her special field is inadequate, must count upon spending increased time in work for the degree.

However, no student will be allowed to continue work toward the doctor's degree for more than five academic years of graduate residence, without a petition approved by the dean of graduate studies. This petition must include a plan and schedule for completion, agreed upon and signed by the student, the research adviser, and the option representative.

*Registration.* Continuity of registration must be maintained until all requirements for the doctor's degree have been completed, with the exception of summer terms and authorized sabbaticals. Registration is required for the quarter in which the thesis defense is undertaken.

*Admission to Candidacy.* On the recommendation of the chair of the division concerned, the dean of graduate studies will admit a student to candidacy for the degree of Doctor of Philosophy after the student has been admitted to work toward the doctor's degree and has been in residence at least one term thereafter; has initiated a program of study approved by the major option and, if needed, by the minor option; has satisfied by written or oral examination the several options concerned, or otherwise shown that he or she has a comprehensive grasp of the major and minor subjects and of subjects fundamental to them; has demonstrated the ability for clear and forceful self-expression in both oral and written English; and has shown ability in carrying on research in a subject approved by the chair of the division concerned. Option regulations concerning admission to candidacy are given in a later section. Members of the Institute staff of rank higher than that of assistant professor are not admitted to candidacy for a higher degree.

Students may demonstrate competence in written English by scoring 5 or above on the TWE examination or by having their final thesis accepted by the faculty. To determine oral competence in English, students from non-English-speaking countries are screened during the fall orientation session. Those who do not pass the screening must enroll in ESL 101 during the fall quarter and must subsequently score at least 50 on the standardized NTS

(National Testing Service) SPEAK Test. Students who score below 50 on the SPEAK Test are urged to continue taking ESL classes; they must pass the SPEAK Test before admission to candidacy. To help students pass this test, ESL courses are held throughout the school year and intensive English is offered in the summer. The Graduate Office will maintain a record of the test scores and will provide them to the option representatives, as needed, to verify that the student has met this requirement. (Note: Other ESL courses are open to all students who want to improve their oral skills, as described on page 450.)

A standard form, obtained from the dean of graduate studies, is provided for making application for admission to candidacy. Such admission to candidacy must be obtained before the close of the second term of the year in which the degree is to be conferred. *The student is responsible for seeing that admission is secured at the proper time.* A student not admitted to candidacy before the beginning of the fourth academic year of graduate work at the Institute must petition through his or her division to the dean of graduate studies for permission to register for further work.

After achieving candidacy, each Ph.D. student should be assigned a thesis advising committee of three or more faculty members. This committee should meet informally at least once a year beginning in the fourth year of graduate study.

Candidacy (and permission to register) may be withdrawn by formal action of the option from a student whose research is not satisfactory, or for other compelling reasons. However, the option must petition through its division chair to the dean of graduate studies before taking such action.



*Final Examination.* Each doctoral candidate shall undergo broad oral examination on the major subject, the scope of the thesis, and its significance in relation to the major subject. The examination, subject to the approval of the dean of graduate studies, may be taken after admission to candidacy whenever the candidate is prepared; however, it must take place at least three weeks before the degree is to be conferred.

The examination may be written in part, and may be subdivided into parts or given all at one time at the discretion of the options concerned. The student must petition for this examination, on a form obtained from the Graduate Office, not less than two weeks before the date of the examination. Ordinarily, more than two weeks are needed for the necessary arrangements. An examination committee should consist of a minimum of four voting members, three of whom must be Caltech faculty. Exceptions to this rule must be approved by the dean of graduate studies in advance of the defense. The date of the examination and the composition of the examining committee will not be approved by the dean of graduate studies until the thesis is submitted in final form—i.e., ready for review by the dean, the members of the examining committee, and the Graduate Office proofreader.

*Thesis.* The candidate is to provide a copy of his or her completed thesis to the members of the examining committee at least two weeks before the final oral examination. The date of the examination and the composition of the examining committee will not be approved by the dean of graduate studies until the thesis is submitted in completed form, i.e., ready for review by the dean, the members of the examining committee, and the Graduate Office proofreader. Registration is required for the term in which the thesis defense is undertaken, but is not normally allowed beyond the last date of the term. Approval of the dean of graduate studies is required for any student seeking to enroll for subsequent terms following the thesis defense. A student may petition the dean of graduate studies for reduced tuition charges if the student supplies a copy of the thesis, schedules the examination, and submits the necessary petitions for the Ph.D. examination prior to 5:00 p.m. on the third Friday of the term in which the examination will be taken.

The last date for submission of the final, corrected thesis to the dean of graduate studies is the fifth week of the succeeding term if the candidate defended his or her thesis during the previous summer or the first or second terms; or two weeks before the degree is to be conferred if the candidate defended his or her thesis during the month of May. A final copy of the thesis is to be submitted in accordance with the regulations governing the preparation of doctoral dissertations, obtainable from the Graduate Office. In addition, it is required that all doctoral candidates submit an electronic copy of their dissertation, which the Caltech Library System will then archive and make available online, as part of the Networked Digital Library of Theses and Dissertations (NDLTD), an international organization that allows researchers to globally search a database of electronic theses and dissertations. For special option regulations concerning theses, see specific graduate options.



Before submitting the final, corrected thesis to the dean of graduate studies, the candidate must obtain approval of the thesis by the chair of his or her division and the members of the examining committee, on a form that can be obtained at the Graduate Office.

With the approval of the option concerned, a portion of the thesis may consist of one or more articles published jointly by the candidate and members of the Institute staff or other coauthors. In any case, however, a substantial portion of the thesis must be the candidate's own exposition of his or her own work.

The use of "classified" research as thesis material for any degree is not permitted. Exceptions to this rule can be made only under special circumstances, and then only when approval is given by the dean of graduate studies before the research is undertaken.

Regulations and directions for the preparation of theses may be obtained from the Graduate Office, and should be followed carefully by the candidate.

## GRADUATE EXPENSES

The tuition and fees charge for all students registering for graduate work is currently $36,135 per academic year, payable in three installments at the beginning of each term. Graduate students who cannot devote full time to their studies are allowed to register only under special circumstances. Students desiring permission to register for fewer than 36 units must therefore petition on the form available from the Graduate Office. If reduced registration is permitted, the tuition for each term is at the rate of $324 a unit for fewer than 36 units, plus $382 for fees per term, with a minimum of $1,146 per term. This tuition credit will only be made for reduced units as of the published Add Day of each term.

The payment of tuition by graduate students is required (a) without reference to the character of the work by the student, which may consist of research, independent reading, or writing a thesis or other dissertation, as well as attendance at regular classes; (b) without reference to the number of terms in which the student has already been in residence; and (c) without reference to the status of the student as an appointee of the Institute, except that members of the academic staff of rank of instructor or higher are not required to pay tuition.

*Unpaid Bills.* All bills owed the Institute must be paid when due. Any student whose bills are past due may be refused registration for the following term. Graduate students with a bursar's bill balance of $1,500 or more will have a hold placed on their transcripts and on their registration for the subsequent term the day before online registration opens. The hold will be released once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.



Information regarding fellowships, scholarships, and assistantships is discussed in the following pages. Students of high scholastic attainment may be offered special tuition awards covering all or part of the tuition fee. Loans also may be arranged by applying at the Financial Aid Office.

*Caltech Card Charges.* If a graduate student owes more than $1,500 at the end of the quarter, the student's ID card will be deactivated on the seventh day of the following quarter and they will be unable to charge any new purchases. Cards will be reactivated once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.

## Expense Summary 2010–11

| | |
|---|---|
| *General:* | |
| Tuition and fees | $36,135.00 |
| *Other:* | |
| Books and supplies (approx.) | $1,000.00 |
| Room: | |
| *Avery House* | |
| Avery House single room | $665.00 per month |
| Avery House suite room | $698.00 per month |
| Plus Avery meal plan (M–F) | $825.00 per term |
| *Catalina apartments* | |
| 4 bedroom apt. | $525.00 per person per month (plus utilities) |
| 2 bedroom apt. | $622.00 per person per month (plus utilities) |
| 1 bedroom apt. | $1,077.00 per apt. per month (plus utilities) |
| Tuition fees for fewer than the normal number of units: | |
| Per unit per term | $ 324.00 |
| Contact Bursar's Office for audit fee. | |

Fees are subject to change at the discretion of the Institute.

*Fees for Late Registration.* Registration is not complete until the student has registered for a program approved by his or her adviser and has paid tuition and other fees. A penalty fee of $50 is assessed for failure to register within five days of the scheduled dates.

A $50 late penalty will be charged by the Bursar's Office for failure to clear a past-due account within five days of the beginning of instruction.

*Honor System Matters.* Monies owed to the Institute resulting from a Graduate Review Board decision may be collected through the Bursar's Office, at the request of the dean of graduate studies.

*Housing Facilities.* The Catalina Central complex provides approximately 152 single rooms in four-bedroom furnished units. Another, Catalina North, has 156 single rooms in two-bedroom furnished units, and Catalina South has 78 single rooms in two-bedroom furnished units, and 29 one-bedroom furnished units. These apartments are also available to married students. In addition, there are 13 spaces for graduate students in Avery House, an innovative residential community of faculty, undergraduates, and graduate students (see page 30).

Rates for housing vary, depending upon the accommodations and services provided. A contract is required to live in these houses for the academic year. Complete information and reservations can be obtained by writing to housing@caltech.edu or to the Housing Office, Mail Code 160-86, California Institute of Technology, Pasadena, CA 91125 or at http://www.housing.caltech.edu.

The Institute also owns a limited number of apartments and single-family houses that are available for rental, on a lease basis, to single or married graduate students or graduate students with families. Because of limited availability, there is a waiting list for these properties. For additional information and sign-up forms, go to http://www.housing.caltech.edu.

Students preferring to live in non-Institute housing typically pay approximately $550–$600 per month in rent for a shared apartment, and somewhat more for a private apartment. Please note that the Institute cannot make negotiations for individual housing off campus.

*Dining Facilities.* Graduate students are granted the privilege of joining the Athenaeum (faculty club), which affords the possibility of contact with fellow graduate students and with others using the Athenaeum, including the Associates of Caltech, distinguished visitors, and members of the professional staffs of the Huntington Library and the California Institute of Technology.

The Chandler Dining Hall, located on the campus, is open Monday through Friday. Breakfast, lunch, and snacks are served cafeteria style. Café at Broad is open for lunch and dinner, Monday through Friday.

*Health Services.* Health services available to graduate students are explained in section one.

## FINANCIAL ASSISTANCE



Caltech offers in each of its options a number of fellowships, tuition scholarships, and graduate assistantships. In general, tuition scholarships may be for full or partial tuition charges; assistantships provide stipends; and fellowships often provide both tuition scholarship awards and stipends. Graduate assistants are eligible to be considered for special tuition awards.

A request for financial assistance is included on the application for admission to graduate standing. Some options will review applications received after the deadline date, but such applicants may be at a disadvantage in the allocation of financial assistance. Appointments to fellowships, scholarships, and assistantships are decided yearly by the student's academic option.

Graduate students receiving any form of financial aid from the Institute are required to report to the dean of graduate studies any financial aid from other sources. With prior written approval from the dean of graduate studies, students may be allowed to accept outside employment if the time commitment does not interfere with their graduate studies. The number of hours per week spent on outside employment must be reported to the dean of graduate studies.

## Graduate Assistantships

Graduate assistants help with teaching, laboratory work, or research that affords them useful experience. Teaching assistantships are for up to 20 hours per week during the academic year and are devoted to preparation, grading, or consulting with students. Students may not, without advance permission from the dean of graduate studies, be a teaching assistant for a course in which they receive credit. Research assistantships are limited to less than 20 hours per week during the academic year and may be greater during the summer. Combined teaching and research assistantships are common. Stipends are based on four 12-week quarters and are paid on the first of each month. Assistantships normally permit carrying a full graduate residence schedule also. Only teaching assistants with good oral English are allowed to teach sections.

All teaching assistants are required to attend teaching-assistant training before payment can be processed. Training sessions occur during orientation week for incoming graduate students and at least once per term for continuing students, including undergraduate students with teaching responsibilities. Contact the Graduate Office for a schedule of training sessions.

Teaching assistants must familiarize themselves with Caltech's policy on harassment (see page 68). Classes should foster academic achievement in a "hassle-free" environment. Teaching assistants should not attempt to date a student in their class, and should disqualify themselves from teaching a section in which a spouse or current partner is enrolled. Any questions should be referred to the dean of graduate studies.

Teaching and research obligations of graduate assistants shall not exceed 50 weeks per year, but may be less depending on departmental policy and the arrangements made by the adviser and the student. Graduate assistantship appointments include regular Institute holidays occurring during specified appointment periods. In addition, when necessary, graduate assistants may arrange for short-term medical disability leave (including maternity leave). Assistants should schedule their vacation and planned disability leaves with their adviser or option representative. Any questions should be referred to the dean of graduate studies.



## Graduate Scholarships, Fellowships, and Research Funds

Students are strongly encouraged to apply for scholarships and fellowships from federal and private agencies and organizations to support their graduate studies. In addition, the Institute offers a limited number of endowed fellowships and scholarships for tuition and/or stipends to graduate students of exceptional ability.

## Loans

Several types of loans are available to graduate students. To qualify for any of these, a student must demonstrate financial need and must maintain satisfactory academic progress in the course of study for which he or she is enrolled. Application forms and further information are available in the Financial Aid Office.

## Satisfactory Academic Progress

In order to continue receiving financial aid at Caltech, graduate students must maintain satisfactory academic progress toward completion of their degree. Continuity of registration must be maintained until all requirements for the degree being sought have been completed, with the exception of authorized sabbaticals.

The Master of Science degree requires at least one academic year of residence at the Institute and 135 units of graduate work with a grade-point average of at least 1.9. Under normal circumstances a master's degree requires a minimum of three academic terms (one year) and cannot take more than two years, without a petition approved by the dean of graduate studies.

The engineer's degree must consist of advanced studies and research in the field appropriate to the degree desired. At least six terms (two years) of graduate residence are required with a minimum 1.9 overall grade-point average. The engineer's degree cannot take more than three years to complete, without a petition approved by the dean of graduate studies.

For the doctor's degree, at least nine terms (three years) of residence are required, but the necessary study and research typically require more than five years. The work for the degree consists of research and the preparation of a thesis describing it, and of systematic studies of an advanced character, primarily in science or engineering.



The requirements for each degree include special regulations established by each option and detailed in the Institute catalog for the year of initial registration. Many options require a C grade or better in particular courses or groups of courses. Hence, a limited number of courses may be repeated while still maintaining a status of satisfactory academic progress and would count toward the 36-unit-per-term requirement. A full-time graduate student must register for (and complete) 36 units per term, including the summer term. Approval of the dean of graduate studies is required before dropping any course that brings a student below 36 units. The treatment of incomplete grades and withdrawals is specified on pages 40–42. Satisfactory academic progress is checked each academic year by the Graduate Office.

The special regulations for the options typically include the completion of specific courses, oral and/or written examinations, petitions, research requirements, etc., by specific times. Satisfactory academic progress is judged by the options against these regu-

lations, and revocation of permission to register may be recommended by the option to the dean of graduate studies prior to or in response to the student's petition for admission to candidacy. Further, even after admission to candidacy, the candidacy (and permission to register) may be withdrawn by formal action of an option for a student whose research is not satisfactory, or for other compelling reasons. However, the option must petition through its division chair to the dean of graduate studies before taking such action.

A doctoral student who has not been admitted to candidacy by the beginning of the fourth year must petition to the dean of graduate studies for permission to register for further work. In addition, no doctoral student will be allowed to register for a sixth year without approval of a petition by the dean of graduate studies. This petition must include a plan and schedule for completion, agreed upon and signed by the student, the thesis advising committee, and the option representative.

Petitions approved by the option and the dean of graduate studies reinstate student eligibility for all financial aid.

### Refund and Repayment Policy

Caltech has established an equitable refund policy for students who find it necessary to withdraw or take a sabbatical from the Institute.

Students who officially withdraw or take a sabbatical from the Institute during an academic term may receive a tuition refund (see pages 147–150). Students living in Caltech housing may also be eligible for a partial refund from the Housing Office.

When granting refunds to financial aid recipients or graduate assistants, it is Caltech's policy to return the refund, in most cases, to the original account.



## PRIZES

*Charles D. Babcock Award*

The Charles D. Babcock Award recognizes a student whose achievements in teaching (or other ways of assisting students) have made a significant contribution to the aeronautics department. The criteria for the award selection are as follows: The award can be made as unscheduled support for a graduate student associated with aeronautics, e.g., for travel to a technical meeting for professional advancement. All aeronautics-associated students are eligible, with preference given to those in the structures and solid mechanics group. The award may be made yearly, as merited. The timing of the award will be as special recognition warrants.

The Charles D. Babcock Award was established in 1992 in memory of Charles D. Babcock, who was professor of aeronautics and applied mechanics until 1987; he served aeronautics as option representative and the Institute as vice provost.

*William F. Ballhaus Prize*
A prize of $1,000 will be awarded for an outstanding doctoral dissertation in aeronautics, to be selected by the aeronautics faculty. This award is made possible by a gift from Dr. William F. Ballhaus, a California Institute of Technology alumnus, who received his Ph.D. degree in aeronautics in 1947.

*Bohnenblust Travel Grants in Mathematics*
Special grants may be awarded to outstanding graduate students in mathematics to enable them to travel in the United States or abroad to further their mathematical education. The mathematics faculty established these awards in 1978 to honor H. F. Bohnenblust, who served Caltech as professor of mathematics, executive officer for mathematics, and dean of graduate studies. Application forms and further details are available in the mathematics office, 253 Sloan.

*Rolf D. Buhler Memorial Award in Aeronautics*
An award of $500 is made annually to a student in the aeronautics master's program whose academic performance was exemplary and who shows high potential for future achievements at Caltech.

The Rolf D. Buhler Memorial Award in Aeronautics was established in 1990 in memory of Rolf Buhler, a 1952 graduate of GALCIT and professor of space flight at the Technical University of Stuttgart in Germany.

*W. P. Carey & Co., Inc., Prizes in Applied Mathematics*
Prizes of up to $1,000 will be awarded by a faculty committee in applied mathematics for outstanding doctoral dissertations. If there is no appropriate candidate, then the awardee can be chosen from pure math. These awards have been made possible by gifts from William Polk Carey and from W. P. Carey & Co., Inc.



*Centennial Prize for the Best Thesis in Mechanical Engineering*
This prize shall be awarded each year to a candidate for the degree of Doctor of Philosophy in mechanical engineering whose doc-toral thesis is judged to be the most original and significant by a faculty committee appointed each year by the executive officer of mechanical engineering. The prize consists of a citation and a cash award of $1,000. This prize is made possible by gifts from alumni following the mechanical engineering centennial celebrations in 2007.

*Richard Bruce Chapman Memorial Award*
A prize of $500 will be awarded annually to a graduate student who has distinguished himself or herself in research in the field of hydrodynamics.

Bruce Chapman was awarded an M.S. from Caltech in 1966 and a Ph.D. in 1970, both in engineering science. This award has been established in his memory by his family and friends.

*Milton and Francis Clauser Doctoral Prize*
An annual prize is awarded to the Ph.D. candidate whose research is judged to exhibit the greatest degree of originality as evidenced by its potential for opening up new avenues of human thought and endeavor as well as by the ingenuity with which it has been carried out. The Milton and Francis Clauser Doctoral Prize is made possible by gifts from the family and friends of these twin alumni, who received bachelor's degrees in physics in 1934, master's degrees in mechanical engineering in 1935, and doctor's degrees in aeronautics in 1937.

*Donald Coles Prize in Aeronautics*
The Donald Coles Prize will be awarded to the graduating Ph.D. student in aeronautics whose thesis displays the best design of an experiment or the best design for a piece of experimental equipment.

*Demetriades-Tsafka-Kokkalis Prize in Biotechnology or Related Fields*
Awarded annually to a Ph.D. candidate for the best thesis, publication, or discovery in biotechnology or related fields at the Institute in the preceding twelve months. Winners are selected by the bioengineering faculty. This award has been made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

*Demetriades-Tsafka-Kokkalis Prize in Entrepreneurship or Related Fields*
Awarded annually for the best business plan or proposal, start-up, thesis, publication, discovery, or related efforts by student(s) in entrepreneurship or related fields at the Institute in the preceding twelve months. This prize is made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.



*Demetriades-Tsafka-Kokkalis Prize in Environmentally Benign Renewable Energy Sources or Related Fields*
Awarded annually to a Ph.D. candidate for the best thesis, publication, discovery, or related efforts by student(s) in benign renewable energy sources or related fields at the Institute in the preceding twelve months. The prize is made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

*Demetriades-Tsafka-Kokkalis Prize in Nanotechnology or Related Fields*
Awarded annually to a Ph.D. candidate for the best thesis, publication, or discovery in nanotechnology or related fields at the Institute in the preceding twelve months. This prize is made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

*Constantin G. Economou Memorial Prize*
Awarded to a chemical engineering graduate student distinguished by outstanding research accomplishments and exemplary attitude while fulfilling candidacy requirements for the Ph.D. degree.

*Everhart Distinguished Graduate Student Lecture Series*
The Everhart Lecture Series is a forum to encourage interdisciplinary interaction among graduate students and faculty, to share ideas about recent research developments, problems, and controversies, and to recognize the exemplary presentation and research abilities of Caltech's graduate students. Lecturers discuss scientific topics at a level suitable for graduate students and faculty from all fields while addressing current research issues. Each fall, three graduate-student lecturers are selected to present their work as part of the Everhart Lecture Series based on each student's dynamic speaking skills, which capture the attention of and convey research material clearly to a diverse technical audience; ability to communicate his or her research field's broader importance; and impact on the scientific community through his or her research. Speakers receive a $500 honorarium and recognition at graduation.

*Lawrence L. and Audrey W. Ferguson Prize*
Awarded to the graduating Ph.D. candidate in biology who has produced the outstanding Ph.D. thesis for the past year.

*Henry Ford II Scholar Awards*
The Henry Ford II Scholar Awards are funded under an endowment provided by the Ford Motor Company Fund. Each award, up to $5,000, will be made annually either to the engineering student with the best academic record at the end of the third year of undergraduate study, or to the engineering student with the best first-year record in the graduate program. The chair of the Division of Engineering and Applied Science names the student to receive the award.



*Graduate Dean's Award for Outstanding Community Service*
This award is made annually to a Ph.D. candidate who, throughout his or her graduate years at the Institute, has made great contributions to graduate life and whose qualities of leadership and responsibility have been outstanding.

*Hans G. Hornung Prize*
This prize is awarded for the best oral Ph.D. defense presentation by a student advised by an aerospace faculty member. The committee to determine the winner is made up of current aerospace engineering students who attend the talks in order to make their recommendation.

*Scott Russell Johnson Prize for Excellence in Graduate Study in Mathematics*
Four prizes of $5,000 will be given to continuing graduate students for excellence in one or more of the following: extraordinary progress in research, excellence in teaching, or excellent performance as a first-year graduate student. The executive officer for mathematics, in consultation with the faculty, determines the recipients. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. '83.

*Scott Russell Johnson Graduate Dissertation Prize in Mathematics*
A prize of $2,000 is awarded for the best graduate dissertation in mathematics. The prize may be split between two students. The executive officer for mathematics, in consultation with the faculty, selects the recipient. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. '83.

*Abdul Kalam Prize in Aerospace Engineering*
This prize is awarded to a student in the aerospace engineering master's program whose academic performance is exemplary and who shows high potential for future achievements.

*Lemelson-MIT Caltech Student Prize*
The Lemelson-MIT Caltech Student Prize is awarded to a Caltech senior or graduate student who has created or improved a product or process, applied a technology in a new way, redesigned a system, or in other ways demonstrated remarkable inventiveness. Students gain invaluable exposure to the science, business, and investment communities through participation in this competition.



*The Herbert Newby McCoy Award*
A cash award is made annually to a graduate student in chemistry to acknowledge an "outstanding contribution to the science of chemistry." The awardee is chosen by a faculty committee, based on solicited nominating packages, and the award-winning research is presented in a formal divisional seminar given by the awardee.

The McCoy award was established in 1965 as a result of a bequest of Mrs. Ethel Terry McCoy to honor her husband, who did pioneering work in the chemistry of rare earths and was associated with Caltech through collaboration with chemists Linus Pauling and Howard Lucas.

*Eleanor Searle Prize in Law, Politics, and Institutions*
The Eleanor Searle Prize was established in 1999 by friends and colleagues to honor Eleanor Searle. The prize is awarded annually to an undergraduate or graduate student whose work in history or the social sciences exemplifies Eleanor Searle's interests in the use of power, government, and law.

*Ernest E. Sechler Memorial Award in Aeronautics*
An award of $1,000 is made annually to an aeronautics student who has made the most significant contribution to the teaching and research efforts of the Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT), with preference given to students working in structural mechanics.

The Ernest E. Sechler Memorial Award in Aeronautics was established in 1980 in memory of Ernest E. Sechler, who was one of the first graduates of GALCIT and who then served as a GALCIT faculty member for 46 years. Throughout his career Sechler was the faculty adviser for aeronautics students. In addition, he made many contributions to structural mechanics in areas ranging from aeronautics to the utilization of energy resources.

*John Stager Stemple Memorial Prize in Physics*
A prize of $500 is awarded annually to a graduate student in physics for outstanding progress in research as demonstrated by an excellent performance on the oral Ph.D. candidacy exam. John S. Stemple was a Caltech physics graduate student when he died; a memorial fund was established from contributions made by the community of Falls Church, Virginia, John's hometown.

*Charles Wilts Prize*
Awarded for outstanding independent research in electrical engineering leading to a Ph.D.

Note: Prizes and awards may be subject to federal and state income tax.



## SPECIAL REGULATIONS OF GRADUATE OPTIONS

### Aerospace

*Aims and Scope of the Graduate Program*
The Institute offers graduate programs in aerospace leading to the degrees of Master of Science in Aeronautics or Space Engineering, Aerospace Engineer, and Doctor of Philosophy. The programs are designed to provide intense education in the foundations of the aeronautical and space sciences, with emphasis on research and analytical, computational, and experimental methods. Entering graduate students should have a thorough background in undergraduate mathematics, physics, and engineering science. Applicants for graduate study are asked to submit Graduate Record Examination scores with their applications.

In working for a degree in aerospace, a student may pursue major study in one of the following areas: physics of fluids, physics of solids and mechanics of materials, structural mechanics, space technology, computational solid mechanics, computational and

theoretical fluid dynamics, aeronautical engineering and propulsion, biomechanics of fluids and solids, technical fluid mechanics, control and materials.

While research and course work in the aerospace option at the Institute cover a very broad range of subjects, a choice of one of the above fields allows students to focus their activities while taking advantage of the flexibility offered by the breadth of interests of the Graduate Aerospace Laboratories (GALCIT). A student with an interest in energy-related subjects will find many suitable courses and research projects of particular use. Subjects of major importance in the efficient use of energy, such as turbulent mixing, drag reduction, and flexible lightweight structures, have historically been the focus of research activity in the aerospace option.

In consultation with his or her adviser, a student may design a program of study in one of the above fields, consisting of the fundamental courses prescribed in the regulations for the separate degrees listed below, and of electives selected from the list of aerospace-related courses. Special attention is called to the list of courses numbered Ae 200 or higher.

*Examinations, Committees, and Student Responsibilities*

To help the student achieve satisfactory progress in his or her academic pursuits, the aerospace faculty provides for the following committee and individual support.

Upon entering aerospace for the master's program, each student is assigned a faculty (course) adviser whose research field matches the interests of the student as described in the latter's statement of purpose in his or her admissions application. This adviser, besides supervising the student's academic performance during that program, may also serve as a personal counselor. During the master's year, the GALCIT director and the option representative, as well as the elected student representative, are also available for counseling (see below).



In order to pursue studies beyond the master's degree and toward the degree of Aerospace Engineer, a student has to select and be accepted by a research adviser. The research adviser may be the former course adviser or a different faculty member. The research adviser and the student select a three-person committee. It is the responsibility of the student to initiate this selection process before the beginning of the post-master's studies. It is also the student's responsibility to have this committee meet three times during the last year of his or her residency before receiving the degree of Aerospace Engineer.

Students wishing to pursue studies leading to the Ph.D. are required to pass a qualifying examination in the first term of the year following completion of their M.S. studies, or, for students entering with an M.S., during the second year of their residency. Having passed the qualifying examination, the student's work con-

tinues to be guided by the three-person committee until he or she is ready to enter candidacy for the Ph.D. The four-member Candidacy Examination Committee shall include the student's research adviser. The Candidacy Committee is chaired by a faculty member other than the research adviser.

Conferral of the Ph.D. degree is contingent on satisfactorily passing the thesis examination before a four-person committee, which may, but does not need to, have the same constitution as the Candidacy Committee.

*Problem and Grievance Resolution within Aerospace*
Students may pursue several avenues for redress concerning personal and academic problems that may arise during their residency. Any member of the supervising committee at the time (three-person or candidacy committee) is accessible for relevant discussion, as are the director and option representative. In addition, two ombudspersons are available, one at the student and one at the faculty level. The student representative is elected annually by the aerospace graduate students at or after the Information Session, which is part of Ae 150 a. In the event that the student representative has completed his or her Ph.D. studies before the election date and left the Institute, the student organizer for Ae 150 may be his or her replacement. A faculty member (at present, an emeritus faculty member), chosen by the aerospace faculty, acts as an ombudsperson available for student contact. The names of the current student and faculty ombudspersons are available in the aerospace office.



*Master's Degree in Aeronautics and Master's Degree in Space Engineering*

*Admission.* Students with a baccalaureate degree equivalent to that given by the Institute are eligible to seek admission to work toward the master's degree in aeronautics or toward the master's degree in space engineering. Applicants are encouraged to indicate their desire to continue studies past the master's degree.

*Course Requirements.* A program of study consists of courses totaling at least 138 units; of these, at least 84 units must be in the following subject areas:

| | |
|---|---|
| Fluid mechanics | 27 units |
| Solid/structural mechanics | 27 units |
| Mathematics or applied mathematics | 27 units |
| Aerospace engineering seminar | 3 units |

An additional 27 units are required as follows: a course in experimental techniques and laboratory work for the master's degree in aeronautics, and a course in space engineering for the master's degree in space engineering. For the space engineering degree, the remaining 27 units of electives are to be chosen from courses at Caltech that support the broader goals of the space engineering

program, subject to the approval of the option representative. Students must have a proposed program approved by their adviser prior to registration for the first term of work toward the degree.

*Admission to More Advanced Degrees*
Students wishing to pursue the more advanced degrees of Aerospace Engineer or Ph.D. must file a petition to continue work toward the desired degree. Students registering for the engineer's degree may transfer to study for the Ph.D. upon satisfactory completion of the same qualifying examination required of those working for the Ph.D. However, once admitted to work for the Ph.D. degree, students are not normally permitted to register for work leading to the engineer's degree. All students working for the engineer's degree or the Ph.D. degree are expected to register for and attend one of the advanced seminars (Ae 208 abc or Ae/AM 209 abc).

*Degree of Aerospace Engineer*
The degree of Aerospace Engineer is considered to be a terminal degree for the student who desires advanced training more highly specialized than the master's degree permits, and with less emphasis on research than is appropriate for the Ph.D. degree.

*Admission.* Students with a Master of Science degree equivalent to that given by the Institute may seek admission to work for the engineer's degree.

*Program Requirements.* The degree of Aerospace Engineer is awarded after satisfactory completion of at least 138 units of graduate work equivalent to the Master of Science program described above, plus at least 135 additional units of advanced graduate work. This latter program of study and research must consist of

- not less than 60 units of research in aerospace (Ae 200);
- three units of an advanced seminar such as Ae 208; and
- satisfactory completion (with a grade of C or better, or Pass) of at least 27 units of aerospace courses numbered Ae 200 or higher, or CE/Ae/AM 108, Ae/ME 120, and Ae/Ge/ME 160, excluding research and seminars.

A proposed program conforming to the above regulations must be approved by the student's adviser prior to registration for the first term of work toward the degree.

A thesis is required based on the research program and may consist of the results of a theoretical and/or experimental investigation or may be a comprehensive literature survey combined with a critical analysis of the state of the art in a particular field.

No student will be allowed to continue to work toward the degree of Aerospace Engineer for more than six terms of graduate residence beyond the baccalaureate degree (not counting summer registrations) except by permission after petition to the aerospace faculty.

*Degree of Doctor of Philosophy*

*Admission.* Students with a Master of Science degree equivalent to that given by the Institute may seek admission to work for the Ph.D. degree. In special cases, students may be admitted to Ph.D. work without first obtaining the master's degree.

*Qualifying Examination.* Because of the broad spectrum in the backgrounds of graduate students entering the Ph.D. program in aerospace, the student must first pass a qualifying examination to determine whether he or she is qualified to pursue problems typical of Ph.D. work. Emphasis in the qualifying examination is directed at determining if the student is properly prepared and qualified to undertake graduate research. The exams will cover the following subjects:

a. Fluid mechanics (Ae/APh/CE/ME 101 abc)
b. Solid mechanics (Ae/AM/CE/ME 102 abc)
c. Mathematics (ACM 100 abc)

The material covered in these examinations is at the same general level and breadth as covered in the corresponding M.S.-level courses. The examinations are offered during one week in the first half of the first term, in the second year of graduate residence at the Institute.

A student is examined orally on all three of these topics. In the event of an unsatisfactory performance, the examining faculty members may permit a repeat examination in the appropriate topics. The repeat examination must be scheduled prior to finals week of the second term and must be completed before the end of the third term of the same year.

*Candidacy*. To be recommended for candidacy for the Ph.D. in aerospace, the applicant must have satisfactorily completed at least 138 units of graduate work equivalent to the above Master of Science program and must pass, with a grade of C or better, 27 units of graduate-level ACM courses beyond ACM 95/100, and complete (with a grade of C or better, or Pass) at least 45 units of aerospace courses numbered Ae 200 or higher, or Ae/ME 120 and Ae/Ge/ME 160, excluding research and seminars. If any of the above subjects were taken elsewhere than at the Institute, the student may be required to pass special examinations indicating an equivalent knowledge of the subject.



In addition to fulfilling these course requirements, the applicant must pass a candidacy examination in the second or third year of residence at the Institute. This examination aims at determining whether the student is successful in integrating formal course work into a mature understanding of fundamental engineering concepts, and at demonstrating his or her professional competence in applying these concepts to problems in advanced research.

*Minor*. No minor is required for the Ph.D. degree. Students are, however, encouraged to take advanced courses appropriate to their particular interests.

*Foreign Languages*. The student is encouraged to discuss with his or her adviser the desirability of studying foreign languages.

*Thesis and Final Examination*. Before graduation, each candidate is required to give a public seminar presenting the results of his or her thesis research. For final examination and thesis completion, see also the general degree requirements and the section on Examinations, Committees, and Student Responsibilities regarding aerospace starting on page 264.

*Subject Minor*

A student majoring in a field other than aerospace may, with the approval of the option representative, elect aerospace as a subject minor. A minimum of 54 units in subjects acceptable to the aerospace faculty is required.

## Applied and Computational Mathematics

*Aims and Scope of the Graduate Program*

Caltech's Computing & Mathematical Sciences department offers an interdisciplinary program of graduate study in applied and computational mathematics leading to the Ph.D. degree. This program is designed to give students a thorough training in fundamental computational and applied mathematics and to develop their research ability in a specific application field. The fields of application include a wide range of areas such as fluid mechanics, materials science, and mathematical biology, engineering applications, image processing, and mathematical finance. The training essential for future careers in applied mathematics in academia, national laboratories, or in industry is provided by completion of the requirements for a Ph.D. degree in applied and computational mathematics.



The research areas and interests of the applied and computational mathematics faculty cover a broad spectrum, including nonlinear dynamics, computational biology, numerical analysis and scientific computing, computational and theoretical fluid mechanics, theoretical materials science, multiscale computations and homogenization theory, computational methods for electromagnetics and acoustics, statistics, signal and image processing, probability theory and stochastic analysis, and dynamical systems and geometric mechanics. As reflected by the faculty research activities, there is a strong emphasis on computational methods for solving challenging problems arising from engineering and scientific applications.

Reflecting the interdisciplinary nature of the program, several different groups, in addition to the applied and computational mathematics faculty, contribute to the teaching and supervision of research. Students in applied and computational mathematics are expected to combine their basic mathematical studies with deep involvement in some field of application. Basic general courses are listed specifically under applied and computational mathematics, and these are to be supplemented, according to the student's

interest, from the whole range of Institute courses in specific areas of physics, biology, engineering, etc.

A regular colloquium provides the opportunity for visitors, faculty, and students to discuss current research.

*Admission*

Each new graduate student admitted to work for the Ph.D. in applied and computational mathematics is given an informal interview on Thursday or Friday of the week preceding the beginning of instruction for the fall term. The purpose of this interview is to ascertain the preparation of the student and assist him or her in mapping out a course of study. The work of the student during the first year will usually include some independent reading and/or research.

*Course Requirements*

All ACM students are required to take a total of 18 nine-unit courses at the graduate level (or the equivalent of 162 units) during their graduate study at Caltech. Among these 18 courses, the following core courses, typically taken during the student's first year of study, are required: ACM 101 abc, ACM 104, ACM 105, ACM 106 abc, ACM 116, and an application elective course. The application elective course in the first year is selected, with the recommendation of the student's adviser, from among a wide range of courses offered by an outside option within the Institute. In the second and third years, students are expected to take graduate-level courses appropriate to their chosen research area. The remaining 81 units would normally include graduate-level ACM or CDS courses such as ACM 113, 201 abc, 210 abc, 216, 217, CDS 140 ab, 202, etc., as deemed appropriate to the student's research program, and which must be selected in consultation with the student's research adviser.



Students who have already taken some of the required courses may use them to satisfy the course requirements, even though the units may not be used to satisfy the total unit requirement for the Ph.D. degree. In addition, the student is required to enroll in ACM 290 for each quarter that he or she is in residence.

*Master's Degree*

Entering graduate students are normally admitted for the Ph.D. program. The master's degree may be awarded in exceptional cases. Of the 135 units of graduate work required by Institute regulations, at least 81 units of advanced graduate work should be in applied mathematics.

*Degree of Doctor of Philosophy*

*The Candidacy Examination.* In order to be recommended for candidacy, the student must, in addition to satisfying the general Institute requirements, pass an oral or written candidacy examination administered by a faculty committee. This examination is offered

during one week at the end of the first year of graduate residence at the Institute, typically near the beginning of the fall term. The material covered in this examination is based on the three core sequences described above. For students who have already taken the required courses before coming to Caltech, the examination can also be based on the substituted courses taken in the first year.

*Advising and Thesis Supervision.* Upon passing the candidacy examination (usually by the end of the second year), the student is required to choose a thesis supervisor who assumes the major responsibility in supervising the Ph.D. thesis. At the same time, an advising committee consisting of three faculty members is formed to help oversee the advising process. This committee should be formed no later than the third year of graduate study. The student's supervisor is part of this committee, but does not chair the committee. The student is encouraged to meet with the committee members informally for advice or suggestions. Joint supervision between two faculty members is also possible, as is seeking a thesis adviser outside the core applied and computational mathematics option, although in this case it is mandatory that an applied mathematics faculty member be nominated as a co-adviser.

Should a disagreement of any kind occur between the student and his or her supervisor as regards the timely completion of the thesis, the student is encouraged to direct his or her concerns to the committee chair. If this is not workable, the student should feel free to consult with the option representative, the executive officer, or an applied and computational mathematics faculty member of the student's choice. If the student's concerns cannot be resolved through consultation with these individuals, the student is encouraged to pursue resolution of his or her concerns through other channels as outlined in Student Grievance Procedure on page 49.



*Submission of Thesis.* On or before the first Monday in April of the year in which the degree is to be conferred, a candidate for the degree of Ph.D. in applied and computational mathematics must deliver a typewritten or printed copy of the completed thesis to his or her research supervisor.

*Final Examination.* The final oral examination is held within four weeks after the submission of the thesis. The examination covers the thesis and related areas.

*Subject Minor in Applied and Computational Mathematics*

The group of courses must differ markedly from the major subject of study and must include 54 units of advanced courses in applied mathematics. The qualifying courses exclude the basic courses listed under ACM, from ACM 100 to ACM 106, although some flexibility is allowed depending upon the option of origin. The student must pass an oral examination whose subject is directly related to the material covered in the qualifying courses. This oral examination will be waived if the student has received a grade of A in every course.

*Subject Minor in Applied Computation*
The subject minor in applied computation is administered jointly by the applied mathematics and computer science options, and is open to graduate students in all options. This minor emphasizes the mathematical, numerical, algorithmic, and programming methods underlying the application of computation—particularly parallel and concurrent computation—to research in science and engineering.

To pursue the applied computation minor, applied mathematics students should seek a minor adviser in computer science; computer science students should seek a minor adviser in applied mathematics; and students in other options should seek a minor adviser in either applied mathematics or computer science. The minor adviser and the student formulate a program of courses individually tailored to the student's background and needs, with the objective that the student achieve a level of competence in specific subjects relevant to applied computation that is comparable to that of candidacy-level graduate students in applied mathematics *and* computer science in these same subjects. These subjects include *at minimum* mathematical and numerical methods, algorithms, and advanced programming, and may also include other areas of particular relevance to a student's research area, such as specialized mathematical methods, computer graphics, simulation, or computer-aided design.

Each proposed program must be approved by a faculty committee composed of the option representatives of applied mathematics and computer science, and one faculty member appointed by the chair of each division from which students are enrolled in the program. The number of course units is variable, with a minimum of 45 units of graduate-level courses. The satisfaction of the intended level of competence is assured by the student's passing an oral examination.



## Applied Mechanics

*Master's Degree*
Study for the degree of Master of Science in applied mechanics ordinarily will be completed in one academic year and must consist of courses numbered 100 or above totaling at least 138 units. The program must include ME 150 abc and one course from among the following: ACM 100 abc, AM 125 abc, or a substitute acceptable to the faculty in applied mechanics. Note that ACM 100 may not be used to fulfill the advanced mathematics requirement for the Ph.D. in applied mechanics. A minimum of 108 units of graduate-level courses must be selected from courses in AM, ACM, Ae, CE, and ME. The M.S. program must be approved by the student's adviser and the option representative for applied mechanics.

Students admitted for study toward a master's degree but interested in pursuing subsequent study toward a Ph.D. degree should also read the section below concerning this degree.

*Degree of Doctor of Philosophy*

Study and research programs for the Ph.D. degree are individually planned to fit the interests and background of the student. A comprehensive research project leading to a thesis is required.

*Advising and Thesis Supervision.* A counseling committee of three faculty members is appointed for each student upon his or her admission to work toward a Ph.D. degree in applied mechanics, in order to advise the student on a suitable course program. One committee member acts as committee chair and interim adviser until this responsibility is assumed by the thesis adviser. This committee must meet during the first and third terms of each year of Ph.D. study.

The thesis adviser and thesis advisory committee provide the majority of mentoring to the student. In addition, the option representative and other members of the faculty are always available to provide advice and mentoring on any aspect of research, progress toward the Ph.D., future careers, and other aspects of life in graduate school and as a professional scientist or engineer.

*Admission to or Continuation in Ph.D. Status.* Newly admitted students, those continuing study toward the Ph.D. degree in applied mechanics, and all other graduate students wishing to become eligible for study toward this degree, must make satisfactory progress in their academic studies each year, as judged by a special joint faculty committee.

*Admission to Candidacy.* To be recommended for candidacy for the Ph.D. degree in applied mechanics, the student must, in addition to the general Institute requirements, meet the following:

- Complete 27 units of research.
- Complete at least 108 units of advanced courses arranged by the student in conference with his or her adviser and approved by the faculty in applied mechanics.
- Pass with a grade of at least C an additional 27 units of course work in advanced mathematics, such as AM 125 abc or a substitute acceptable to the faculty in applied mechanics.
- Pass a two-part oral candidacy examination in the second academic year of graduate residence at the Institute.

*Thesis and Final Examination.* A final oral examination will be given after the thesis has been formally completed. Copies of the completed thesis must be provided to the examining committee at least two weeks prior to the examination. This thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in his or her specialized field of research.

*Subject Minor*

A student majoring in another branch of engineering, or another division of the Institute, may elect applied mechanics as a subject minor, with the approval of the faculty in applied mechanics and the faculty in his or her major field. The group of courses shall

differ markedly from the major subject of study or research, and shall consist of at least 54 units of courses approved by the faculty in applied mechanics. The student must pass an oral examination that is separate from the examination in the student's major.

## Applied Physics

*Aims and Scope of the Graduate Program*
The faculty in applied physics anticipate that a professional in the field will be able to solve problems of a physical nature by using a combination of analysis, engineering tools, and technological innovation. Graduate study in applied physics at Caltech is therefore designed to cover considerable ground in sufficient depth to prepare the student broadly for any technical challenge that lies ahead. Completion of core preparatory classes during the first two years is normally followed by an additional three years of independent and original research culminating in the Ph.D. The goals of this program are to develop competence in a chosen field of specialization; to develop tools with which to assess problems outside one's field of specialization; to develop sufficient strength in the physical sciences for self-education beyond formal training; and to cultivate the motivation and foresight to become a productive and influential leader. As such, the graduate program in applied physics is strictly a doctoral program; students seeking a terminal master's degree should not apply.

*Degree of Doctor of Philosophy*
In preparation for the candidacy exam, which must be taken prior to the start of the third year in residence, the student must obtain a minimum of 135 units from the following list of core courses: Ph 106; Ph/APh/Ch 125; ACM 101 or AM 125 or Ph 129; APh 105 or Ph 127; and one additional three-term sequence, which may include Ae/APh/CE/ME 101, APh 114, APh 115A, Ph 156, or BE/APh 161/162. All first-year graduate students are also required to attend the weekly seminar class, APh 110 ab, to learn about ongoing research projects with the applied physics option. Students wishing to substitute more advanced material for the courses listed above must obtain prior approval from the option representative. In preparation for candidacy, students are also strongly encouraged to sample more advanced courses in their subfield of interest, including but not limited to APh 130, APh 131, APh 132, Ph 135, Ph 136, EE/APh 180, APh/EE 183, APh 190, and Ph/APh 223. The student's research adviser or the option representative can be consulted for additional recommendations. No more than 27 units of research in APh 200 may be counted toward this limit. Only courses in which the student has obtained a grade of C or higher can be counted toward this sum.

To be recommended for candidacy to the doctoral program, a student must satisfactorily complete the three requirements below:

- *Demonstrate competency in the following basic areas of physics and engineering* at the level indicated:
  1. Classical Physics: Mechanics and Electromagnetism (Ph 106)
  2. Quantum Mechanics (Ph/APh/Ch 125)
  3. Mathematical Methods (ACM 101 or AM 125 or Ph 129)
  4. Statistical Physics and Thermodynamics (APh 105 or Ph 127)
  5. Biophysics or Fluid Physics or Plasma Physics or Solid-State Physics (Ae/APh/CE/ME 101, APh 114, APh/Ph 115, APh 156 or BE/APh 161 and 162).

The student will also be expected to demonstrate proficiency for clear and precise self-expression both in oral and written English.

- *Oral examination*. This examination must be taken before the beginning of the student's third year in residence. The student will be expected to deliver a half-hour oral presentation describing his/her research to date and to answer questions related to this work. This portion of the examination will be followed by a more open-ended discussion to test general proficiency in various subfields of applied physics. Students who fail the oral examination on their first attempt will be given additional guidelines for further study and an opportunity to retake the examination a second and final time if the committee so recommends. Should a student fail the oral examination a second time, he/she cannot continue with doctoral studies leading to the Ph.D. Upon recommendation of the examining committee, however, the student may be granted a terminal master's degree.
- *Research proposal.* The student must have selected a thesis adviser and have completed a minimum of 18 units of research activity under his/her direction by the end of the second year in residence. At the oral examination, the student will discuss the research topic of choice, describe progress to date, and present a research plan for further study. Students whose research component is deemed insufficient or unsatisfactory will be asked to retake the candidacy exam a second time.

Students who fulfill these three requirements will have successfully completed the candidacy exam and will receive a master's degree in applied physics.

*Thesis and Final Examination.* The candidate shall undergo a broad oral examination in the field, to include the subspecialty represented by the thesis and the significance of its findings to the field. This oral examination will be administered at least two weeks after the doctoral thesis has been presented in final form so that the examining committee has sufficient time to review its content. This examination must be taken at least three weeks prior to the date on which the degree will be officially conferred.

*Subject Minor*
Graduate students majoring in other fields may elect a minor in applied physics. In addition to general Institute requirements, the student must complete with a grade of B– or higher 81 units of courses in applied physics above the 100 level, excluding APh 200. Students cannot use courses required by their major option in fulfillment of this requirement. Students interested in a minor must receive prior approval from the option representative in applied physics, who will review and approve the proposed course of study. It is recommended that this course of study include advanced courses spanning different subfields of applied physics.

## Astrophysics

*Aims and Scope of the Graduate Program*
Modern astronomy—certainly as practiced at Caltech—is essentially astrophysics. With the goal of understanding the physical processes that govern the universe, its constituents, and their evolution, astronomy uses the apparatus and methodology of physics to gather and interpret data. In what follows, we use the terms astronomy and astrophysics interchangeably.

The primary aim of the graduate astrophysics program at Caltech is to prepare students for creative and productive careers in astrophysical research. The astrophysics program emphasizes independent research by graduate students, who are free to pursue study in virtually any area of astrophysics. The opportunity exists to take advantage of the many observational facilities owned and operated by Caltech.



*Admission*
Incoming students should have a strong background in physics, and although a good preparation in astronomy is helpful, this is not required for admission to the graduate program. All applicants, including those from foreign countries, are requested to submit Graduate Record Examination scores for verbal and quantitative aptitude tests and the advanced test in physics.

*Master's Degree*
While the option does not offer a master's degree program in itself, students who fulfill the general Institute requirements for such a degree, and the specific option requirements (see below), can receive a master's degree, either en route to a final Ph.D. degree if admitted to candidacy, or as a terminal degree if the candidacy requirements are not met.

The choice of astronomy and other science elective courses must be approved by the department. At least 36 units of the 135 units must be selected from Ay 121–127. The courses Ph 106, Ph 125, and Ph 129 may be required of those students whose previous training in some of these subjects proves to be insufficient. At least

27 units of advanced courses in fields other than astronomy are required.

*Degree of Doctor of Philosophy*

*Astrophysics Program.* The student's proposed overall program of study must be approved by the department during the first year. The following are required of all students for candidacy: Ay 121, Ay 123, Ay 124, Ay 125, Ay 126, and Ay 127. The student should take these courses in the first year. Students must also take at least one term of Ay 122 unless exempted by the executive officer or option representative. Also required are research and reading projects. Credit for this work will be given under courses Ay 142 and Ay 143.

*Physics Program.* The student's program during the first two years of graduate study should include at least 36 units of physics courses, exclusive of Ph 106, Ph 125, and Ph 129, and should include Ph 136 a and Ph 136 b, unless specifically exempted by the option representative or executive officer. Cross-listed courses (e.g., Ph/Ay) in general do not count toward the physics units requirement, unless specifically allowed by prior consultation between the student, the instructor, and the student's option representative. This requirement may be reduced on written approval of the department for students who take substantial numbers of units in Ph 106, Ph 125, and Ph 129. Students in radio astronomy may substitute an advanced course in electrical engineering or applied mechanics for up to nine units of the required 36 units of physics. Theoretical astrophysics students should include at least 54 units of physics courses in their programs. Students in planetary physics may substitute appropriate advanced courses in geophysics and geochemistry. All the above courses must be passed with a grade of C or better, or a P upon prior written permission from the option representative to take the course pass/fail.



*Other Requirements.* An ability to explain concepts and to verbally present one's work is vital to a successful career in research and/or teaching. To this end, all graduate students in astrophysics are required to serve as teaching assistants during their second year, and to make oral presentations as part of the course Ay 141, required of all students in their second year and all subsequent years.

*The Minor.* It is recommended that students take a subject minor in physics. Other fields in which subject minors are taken include geology or engineering, depending on the student's field of specialization.

*Language Requirement.* Although the department believes that knowledge of foreign languages is generally useful, there is no formal foreign-language requirement. However, graduate students for whom English is a second language may be required to demonstrate fluency in oral and written English at the time of

their candidacy exam. The examining committee will administer a test when this is deemed necessary.

*Admission to Candidacy.* To be recommended for candidacy for the Ph.D. degree in astrophysics, a student must, in addition to meeting the general Institute requirements,

- complete satisfactorily 36 units of research (Ay 142) or reading (Ay 143);
- pass with a grade of B or better, or by special examination, Ay 121, Ay 123, Ay 124, Ay 125, Ay 126, and Ay 127; and also Ay 122 for observational astronomy students;
- pass a general oral examination (see below);
- pass a thesis-related examination (see below);
- complete the physics course requirement (see above);
- satisfy a teaching requirement (at least one term as a GTA);
- fulfill the language requirement if applicable (see above); and
- be accepted for thesis research by a member of the faculty.

In fall of their second year, all students are required to take a general oral candidacy examination. Students will be examined on the substance and status of, as well as their performance on, a research project, which should be started not later than the summer following the first year. They will further be examined on their broad understanding of current topics in, and fundamentals of, astrophysics. Both of these aspects of the examination are intended to evaluate the candidate's aptitude for a research career in astrophysics. In addition, at the discretion of the executive officer, students who have not done well in one, or at most two, areas covered in the Ay 120 course series during their first year will be retested in these areas during the examination. Students must pass all of the aspects of this examination, as judged by the faculty committee conducting it, in order to continue in the Ph.D. program.



Students who receive more than two C (or lower) grades in the Ay 120 series, or who do not pass the general candidacy examination described above, will not be able to continue in the Ph.D. program. They may receive a terminal master's degree, provided that they fulfill the requirements for it (see above).

*Advising and Thesis Supervision.* By the summer of their first year, students should be spending most of their time on research. During their first two years, students are free to work with any faculty they wish, on one or more projects. However, by the summer of their second year at the latest, they should have defined a thesis project and been accepted by a faculty research adviser for that project (in cases where the thesis involves multiple projects, a second faculty adviser may supervise part of the research, but one must be selected as primary adviser). An oral candidacy exam dealing with the student's proposed thesis research should be taken before the end of the second term of the third year. The date and time of the exam are the responsibility of the student to arrange. The examining committee is chosen by the executive officer in

consultation with the student's adviser. It will stand until the final examination, and be charged with ensuring that satisfactory progress toward the Ph.D. is being made.

If the candidate does not pass the oral candidacy exam, then the examining committee may at its discretion offer the candidate a second oral examination. This examination must be successfully completed by the end of the third term of the third year. Under no circumstances will students be permitted to continue beyond the third year without successful completion of all candidacy requirements.

After the oral candidacy exam, the adviser and the student together have primary responsibility for the student's progress and career development. To ensure that these remain on course, both student and adviser must submit annual progress reports to the executive officer (or in the case of a conflict of interest, to the astrophysics option representative or the division chair). If at any stage the student, the adviser, or the executive officer feels that there are serious problems developing, they may consult in confidence with the astrophysics option representative, the executive officer, or the division chair. They may also request a meeting of the oral candidacy exam committee or seek the advice or help of other faculty members. Students may also seek confidential advice and help from the Counseling Center and the Ombuds Office.

*Final Examination.* A final draft of the thesis must be submitted at least six weeks before the commencement at which the degree is to be conferred. At least two weeks after submission of the thesis, the student will be examined orally on the scope of his or her thesis and its relation to current research in astrophysics. The examination will be conducted by a committee selected in the same way as the oral candidacy committee. The examination should occur before the end of the fifth year. Only in rare circumstances will permission be granted to continue in a sixth year. Such permission requires a written petition to the executive officer.



Typical timeline:

Year 1: Ay 121, Ay 123–127; at least three advanced physics courses; reading and independent study. Begin research.

Year 2: Early fall—general oral candidacy examination. Research projects; select thesis and adviser. Fulfill teaching requirement. Complete 36 units of physics (54 for theorists); Ay 122 if applicable; optional advanced astronomy courses. Ay 141.

Year 3: Take oral candidacy exam on thesis before end of second term. Annual report from student and adviser. Ay 141.

Year 4: Annual report from student and adviser. Ay 141.

Year 5: Annual report from student and adviser. Ay 141. Complete Ph.D. thesis before end of year 5. Final oral examination.

*Subject Minor*
The program for a subject minor in astrophysics must be approved by the department before admission to candidacy. In addition to general Institute requirements, the student must complete satisfactorily, with a grade of C or better, 45 units in advanced courses in astronomy.

## Behavioral and Social Neuroscience

*Aims and Scope of the Graduate Program*
The application of neuroscientific methods to the social sciences is a new frontier at the intersection of the social and natural sciences. Caltech is one of the few places in the world with deep expertise in neuroscience, behavioral economics, and political science. We have built bridges with faculty members in other divisions who are leading researchers in neuroscience. For these reasons, we are in a unique position to train Ph.D. students in this new interdisciplinary area.

Students in the behavioral and social neuroscience (BSN) program receive in-depth training both in neuroscience and rigorous social science methods, and thus will be in a position to make significant research contributions at the intersection of the two disciplines.

*Master's Degree*
Entering graduate students are admitted to the Ph.D. program, and will earn the M.S. degree after successful completion of 135 units of course work. The program does not admit students who plan to obtain an M.S. degree only, but a student who does not go on to achieve a Ph.D. may leave with a terminal master's degree.



*Admissions*
Admission to the Caltech Ph.D. program is highly competitive, and those who are admitted have excellent GRE scores, impressive academic records as undergraduates, and highly supportive letters of recommendation. Entering students are expected to have a strong background in mathematics, and to have completed courses in calculus at the levels of Ma 2, linear algebra, and mathematical statistics.

*Course Program*
The program is designed to enable students to earn their Ph.D. in five years, although it is sometimes possible to finish in four years. During their initial three years in the program, students are expected to acquire competence in the core areas of neuroscience, statistics and econometrics, and either economics or political institutions/political behavior. The fourth and fifth years focus on research and writing, culminating in a dissertation and the granting of a Ph.D.

The first-year curriculum consists of the following required course work: decision theory, game theory, and social choice (SS 201 abc), econometrics (SS 222 abc), behavioral and social neuroscience (Bi/Psy 102 ab), neurobiology (Bi/CNS 150), computational neuroscience (Bi/CNS/CS 187), plus lab rotations 1–3 (with the third lab rotation completed during the summer). Courses are primarily nine units each, so students must register for at least 36 units each quarter. In order to make satisfactory progress, students must complete each class with a grade of B or better. Students should meet with the director of graduate studies (DGS) at least once a quarter to discuss their program and the progress they are making, and to address any difficulties that they might be encountering.

The second-year curriculum consists of the following required course work: completion of the course sequences in foundations of economics (SS 205 abc) or political institutions and political behavior (SS 202 abc), as well as the graduate writing seminar (SS 281). Following the 36-unit requirement per term, the remaining units each term will be achieved by taking SS 300. Students must receive an average grade of B or better for course work or a pass for SS 300.

During each of the first and second quarters of the third-year curriculum, students take 15 units of research in social science (SS 300), supervised by their primary adviser, and at least two other graduate social science courses. One of these courses must be modern topics in social science (SS 280). This course exposes students to influential works in areas of social science that are not typically covered in the first- and second-year courses. In the third quarter, students must enroll in at least one advanced social science course along with 24 units of SS 300.



Beginning in their third year and in all subsequent years, all students should also enroll in the three-unit graduate student seminar (SS 282) every quarter. Every student must make a presentation in this class at least once a year. The SS 300, 280, and 282 courses are all taken on a pass-fail basis.

The fourth year is a yearlong thesis workshop, which means students need to register for 33 units of SS 300 and three units of the graduate student seminar SS 282, all on a pass-fail basis.

During their fifth and final year in the program, students focus on obtaining a job (or a postdoctoral position) and on completing and defending their dissertation. Early in the first term, students need to complete a job-market paper, practice presenting that paper at an optionwide seminar, and assemble and mail job applications.

*Progress Review Leading to Candidacy*

At the end of the third quarter of the first year, students are required to take written preliminary examinations in theoretical foundations of social science (SS 201 abc) and econometrics

(SS 222 abc). Each part requires three to four hours to complete. The exams are written by the instructors of the first-year course sequences, but are graded by the entire social science faculty. The results given are honors, pass, and fail. Students must achieve at least a pass in both parts. Failure to do so may lead to termination from the program, but the faculty may also decide to give students who fail the opportunity to retake any or all parts of the exam before the beginning of the second year.

By the end of the second year, students must also satisfactorily complete and pass the prelim corresponding to either microeconomics (SS 205 abc) or political science (SS 202 abc), depending on which sequence they select to take. Again, each part requires three to four hours to complete. The exams are written by the instructors of the second-year course sequences but are graded by the entire social science faculty. The results given are honors, pass, and fail. Students must achieve at least a pass in both parts. Failure to do so may lead to termination from the program, but the faculty may also decide to give students who fail the opportunity to retake any or all parts of the exam before the beginning of the third year.

Also, by the end of their second year, students are required to submit a research paper (which may be coauthored) to the DGS after having it approved by their two-person committee. During the spring quarter of the second year, students should enroll in SS 300, a seminar devoted to work on their second-year paper, and SS 281, which focuses on scholarly writing and presentation. The primary adviser and second committee member will monitor and evaluate the progress on the second-year paper. If the two faculty reviewers find that a student's second-year paper is satisfactory, the student advances to the third year. If they do not, the social science faculty as a whole will decide whether or not the paper is satisfactory. If they decide it is not, they may also vote to terminate the student from the program.



Third-year students must write a research paper (which may be coauthored), submit it to the DGS, and present it to the faculty by the end of the third quarter. The paper and the presentation must demonstrate to the faculty that the student is capable of undertaking original research and presenting it to a scholarly audience. Ideally, the third-year paper leads directly into dissertation research, but it is not a requirement that this be the case.

After the completion of the third-year paper presentation, the social science faculty evaluates the student's overall performance and research potential. This review is based primarily upon the third-year paper, but the faculty also verifies that the student has satisfactorily completed all previous requirements. If this evaluation is favorable, the student is admitted to candidacy for the Ph.D. At this point, the student needs to file candidacy papers with the dean of graduate studies. If this evaluation is unfavorable, the student may be terminated from the program.

*Organization of the Thesis Committee*

By February 1, second-year students should have decided upon the general area in which they intend to pursue research and should therefore select a primary adviser whose work is related to their research interests. The adviser must be a faculty member in behavioral and social neuroscience at Caltech. The primary adviser will serve as chair of their dissertation committee. It is possible to change advisers if a student's research interests change. A second committee member, who should be a faculty member in either BSN or in social science, should be chosen by June 1 of the second year.

By the end of the third year, all students, in consultation with their advisers, should select a third committee member. This choice should be based on the content of ongoing dissertation research. It is not necessary that the third member be responsible for the full breadth of research covered by the dissertation, and in many cases the third member is selected to provide specialized help, e.g., in econometrics. Committee members may be chosen from outside the social science faculty, but such choices must be approved by the DGS.

Also by April 1 of the fourth year, students are required to have finalized the membership of their thesis committee. The committee consists of four members, one of whom is assigned by the chair of the Division of the Humanities and Social Sciences. Two members of the committee must be members of the social science faculty, and the committee must include at least one member of the social science faculty who does not specialize in neuroscience.

*Ph.D. Degree Requirements*

Satisfactory progress during the fourth and fifth years toward completion of the Ph.D. consists of the following.



By October 15 of the fourth year, a dissertation prospectus must be developed that outlines the proposed dissertation and sets a tentative schedule indicating when the various components of the dissertation are expected to be completed. This prospectus must be approved by the adviser and the second and third committee members before it is filed with the DGS.

Also, by April 1 of the fourth year, all students are required to convene a thesis proposal seminar with their adviser and other committee members. In this seminar, they are to report on the current status of their dissertation research and outline a plan and timeline for completing it. Students and their committee should thus reach a clear, mutual understanding as to what additional work needs to be done to complete and to successfully defend their dissertation. While the committee chair/adviser is primarily responsible for monitoring progress on the dissertation, students also need to consult regularly with the other members of their committee and keep them informed as to the progress they are making and any problems they are encountering. It is also expected that in the fall of their fifth year, students will present an option-wide seminar in order to prepare for the job market.

After the dissertation has been completed, students, in consultation with their adviser, must schedule the oral defense. Students must provide a written copy of their dissertation to the DGS at least two weeks prior to the oral defense date. The dissertation is expected to represent publishable, original research with a coherent theme. Successful completion implies that the faculty has certified that the student is a trained, professionally knowledgeable, and potentially productive scholar in his or her chosen area of work.

## Biochemistry and Molecular Biophysics

*Aims and Scope of the Graduate Program*
An integrated approach to graduate study in biochemistry and molecular biophysics has been organized primarily by the Division of Biology and the Division of Chemistry and Chemical Engineering. The curriculum is designed to provide a broad background in biochemistry and biophysics of macromolecules and molecular assemblies, in addition to an appropriate depth of knowledge in the field selected for the Ph.D. thesis research.

*Admission*
The option in biochemistry and molecular biophysics is open to students with undergraduate degrees in biochemistry, biology, chemistry, biophysics, physics, engineering, and related areas. All applicants for admission, including those from foreign countries, are required to submit the verbal, quantitative, and analytical scores for the Graduate Record Examination and are also strongly urged to submit the results of an advanced test in a scientific field. Applicants whose native language is not English are required to submit results of the TOEFL exam and, after admission, are required to satisfy the English language requirements of the Institute.



*Master's Degree*
Students are not normally admitted to work toward the M.S. degree. In special circumstances, the M.S. degree may be awarded, provided Institute requirements are met. In general, the degree is not conferred until the end of the second year of residence.

*Degree of Doctor of Philosophy*
The Option Graduate Study Committee will counsel and oversee the student's progress upon admission to the graduate program. In the first year of graduate study, the course requirement consists of a sequence of three core courses covering the biochemistry and biophysics of macromolecules and molecular assemblies (BMB/Bi/Ch 170 abc). These courses will expose the student to contemporary issues in biochemistry and molecular biophysics, and to the tools and methods that are essential for research in this area.

Research advisers are normally selected at the end of the first year. In consultation with their adviser, students are expected to take three additional advanced courses of nine or more units in the first and second years that are appropriate for their particular research interests.

*Laboratory Rotations.* In consultation with the Option Graduate Study Committee and individual professors, students will choose three laboratories in which to do short research projects during their first year of residence. These laboratory rotations are designed to provide the student with an introduction to different areas of biochemistry and molecular biophysics. It is possible to waive some or all of the rotations by petitioning the Option Graduate Study Committee.

*Admission to Candidacy.* By the end of the sixth term of residency, the student will take an oral examination to assess mastery of the field of biochemistry and to evaluate research progress. As part of this examination, each student will submit a written research report summarizing the progress in their research, and an original research proposition in a field outside the student's chosen field of research. A candidacy examination committee will be assembled by the Option Graduate Study Committee to administer the examination. When the student advances to candidacy upon successful completion of the exam, this committee will become the thesis advisory committee and will meet with the student once a year to evaluate research progress. This committee will also serve as the Ph.D. thesis examination committee.

*Thesis and Final Examination.* Thesis research will be carried out under the direction of one or more faculty members in the biochemistry and molecular biophysics option. The thesis defense will consist of a thesis seminar, followed by an examination by the Ph.D. thesis committee.



## Bioengineering

*Aims and Scope of the Graduate Program*

The bioengineering graduate program trains doctoral candidates to unite engineering analysis and synthetic approaches to solve frontier problems in biological engineering from molecular to organismal length scales. Ph.D. candidates must satisfy course work and qualifying exam requirements for one of three tracks:

1. the devices and imaging track, focusing on the design and fabrication of devices for manipulating, imaging, analyzing or regulating biological systems;

2. the mechanics track, focusing on elucidating the role of forces and flows in biological development, function and disease, and in exploiting this understanding to engineer biological and nonbiological mechanical systems based on these principles;

3. the synthetic and systems biology track, focusing on the fundamentals of biological circuit design at the molecular, cellular,

and multicellular levels, emphasizing both the physical and information-processing aspects of biological circuits.

The goal of the doctoral program is to prepare students to become leading scientists and engineers in academia and industry.

*Master's Degree*

Students are not admitted to work toward the M.S. degree. In special circumstances, the M.S. degree may be awarded, provided Institute requirements are met. In general, the degree is not conferred until after admission to candidacy for the Ph.D. degree.

*Degree of Doctor of Philosophy*

In addition to satisfying the general Institute requirements, candidates for a Ph.D. in bioengineering at Caltech must satisfy the following requirements.

*Course Requirements.* Each candidate must satisfy the course-work requirements for one of the three tracks. These requirements are intended to build upon undergraduate training and to complement concurrent research activities. All students must maintain a course load of 36 units each term during the first year, and receive a grade of C or higher in each course. An incoming student with prior proficiency in any required course can instead take an elective (including research rotations) with the approval of the option representative. However, all students will be responsible for the required material during the qualifying exam.

Devices and Imaging track (Year 1 only)

- BE 262, Physical and Synthetic Biology Boot Camp: prior to first term
- Math: Three terms selected from ACM 100 abc, AM 125 abc
- Biology: BE 152, BE/APh 161
- Core: Two terms selected from BE/APh/Ph 181, Bi/BE 177, EE/BE 166, EE/BE 185
- Electives: Three terms selected from Ae/APh/CE/ME 101 abc, Ae/AM/CE/ME 102 abc, AM/CE 151 ab, APh 109, APh/EE 130, APh/EE 132, BE/APh 162, BE/Ae 243, Bi/Ch 110, Bi/Ch 111, Bi/Ch 113, Bi 145 ab, Bi/CNS 150, Bi/BE 227, ChE 103 abc, ChE/BE 163, CDS 110 ab, CDS 140 ab, EE/APh 131, EE/BE 166, EE/BE 185, EE 187, Ph 106 abc, Ph/EE 118 ab, Ph 127 abc
- Research: Two terms of BE 200

Mechanics track (Year 1 only)

- BE 262, Physical and Synthetic Biology Boot Camp: prior to first term
- Math: ACM 100 abc
- Biology: Two terms selected from Bi 145 ab, BE 152, BE 157, BE 159, BE/APh 161

- Core: Five terms of mechanics with at least two selected from Ae/APh/CE/ME 101 abc, ChE 103 abc, ChE 151 ab, ChE 174, and at least two selected from Ae/AM/CE/ME 102 abc, ChE/Ch 164, Ph 127 abc
- Research: Two terms of BE 200

Synthetic and Systems Biology track (Year 1 only)
- BE 262, Physical and Synthetic Biology Boot Camp: prior to first term
- Math: ACM 100 ab and one term selected from ACM 100 c, ACM/EE 116, ACM/ESE 118, CDS 110 a, or ChE 105
- Biology: Bi/Ch 110, Bi/Ch 111, Bi/BE 250 c
- Core: BE 159, BE/APh 161, ChE/BE 163
- Research: Research rotations in three labs BE 200

*Research Rotations.* One-term research rotations allow first-year bioengineering graduate students to sample relevant research activities in several labs before selecting a Ph.D. adviser. Research rotations are required in the synthetic and systems biology track and highly recommended in the other tracks. Rotations should be organized by each student in collaboration with individual faculty.

*Adviser Selection*. Students are expected to select a Ph.D. adviser by the end of the third term of the first academic year. Each student is individually responsible for finding an appropriate adviser. Advisers may be chosen from the list of BE faculty, or from any of the faculty in the Division of Engineering and Applied Science, Division of Chemistry and Chemical Engineering, and Division of Biology. Advisers in other divisions may be chosen in consultation with the BE option representative.



*Qualifying Examination.* An oral qualifying examination will be administered to all bioengineering graduate students during the summer term following the first year of course work. Each student will be examined on three subjects reflecting the required course work in the selected track:

devices and imaging track: math, biology, either devices or imaging;

mechanics track: math, biology, either solid, fluid, or statistical mechanics;

synthetic and systems biology track: math, biology, core sequence.

*Admission to Candidacy*. Before the end of the spring term of the second year of residency, each student must prepare a candidacy report and pass an oral candidacy exam. The report should be brief, describing research progress to date and outlining plans for the remaining doctoral research. The committee must be composed of three faculty, plus the adviser(s), including a minimum of two bioengineering faculty. The candidacy report should be submitted to the committee members at least one week before the oral exam. The student who fails to satisfy the candidacy requirements by the

end of the second year in graduate residence will not be allowed to register in subsequent terms except with special permission from the option representative.

*Thesis Examination*. A final oral examination will be given after the thesis has been formally completed. The exam will consist of a public research presentation followed by a private defense with an exam committee consisting of at least three professors in addition to the adviser(s). The thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in his or her specialized field of research.

## Biology

*Aims and Scope of the Graduate Program*

Graduate students in biology come with very diverse undergraduate preparation—majors in physics, chemistry, mathematics, or psychology, as well as in biology and its various branches. The aims of the graduate program are to provide, for each student, individual depth of experience and competence in a particular chosen major specialty; perception of the nature and logic of biology as a whole; sufficient strength in basic science to allow continued self-education after formal training has been completed and thus to keep in the forefront of changing fields; and the motivation to serve his or her field productively through a long career.

In accordance with these aims, the graduate study program in biology includes the following parts: (a) the major program, which is to provide the student with early and intense original research experience in a self-selected subject of biology, supplemented with advanced course work and independent study in this subject; and (b) a program of course work designed to provide well-rounded and integrated training in biology and the appropriate basic sciences, which is adjusted to special interests and needs. An individual program will be recommended to each student in a meeting with the student's advisory committee (see below). The Division of Biology does not encourage applications from students who have pursued undergraduate study in biology at the Institute, because the broader perspective to be gained from graduate study in a different setting is considered to be essential for the full development of each student's potential. Exceptions to this policy may be considered by the faculty of the division if there are circumstances that indicate that it would be in the best interests of a student to pursue graduate study at the Institute.



*Admission*

Applicants are expected to meet the following minimal requirements: mathematics through calculus, general physics, organic chemistry, physical chemistry (or the equivalent), and elementary biology. Students with deficient preparation in one or more of these categories may be admitted but required to remedy their

deficiencies in the first years of graduate training, with no graduate credit being granted for such remedial study. This will usually involve taking courses in the categories in which the student has deficiencies. In certain instances, however, deficiencies may be corrected by examinations following independent or supervised study apart from formal courses. Furthermore, the program in biology is diverse, and in particular fields such as psychobiology and experimental psychology, or in interdisciplinary programs, other kinds of undergraduate preparation may be substituted for the general requirements listed above.

When feasible, visits to the campus for personal interviews will be arranged before a final decision for admission is made. Graduate Record Examinations (verbal, quantitative, and an advanced test in *any* science) are required of applicants for graduate admission intending to major in biology. Applicants are encouraged to take these examinations and request that the scores be transmitted to Caltech, in November or earlier, to ensure unhurried consideration of their applications.

*Master's Degree*

The biology division does not admit students for work toward the M.S. degree. In special circumstances the M.S. degree may be awarded, provided Institute requirements are met. In general the degree is not conferred until the end of the second year of residence. The degree does not designate any of the disciplines of the division, but is an M.S. in biology. The 135 units required by the Institute must include Bi 250 ab and Bi 252.

*Degree of Doctor of Philosophy*



*Major Subjects of Specialization.* A student may pursue major work leading to the doctoral degree in any of the following subjects: genetics; cellular biology and biophysics; immunology; cellular and molecular neurobiology; integrative neurobiology; developmental biology; and molecular biology and biochemistry.

At graduation, a student may choose whether the degree is to be awarded in biology or in the selected major subject. As part of their Ph.D. program, students may complete a minor in another graduate option, in accordance with the regulations of that option. Students should consult with their advisory committee in planning such a program.

*Initial Advisory Committee.* At the start of the first year of study, incoming students meet with the option representative or faculty member(s) specified by the option representative. The purpose of this meeting is to assist the student in organizing laboratory rotations, and to discuss what additional course work is desirable in light of the student's past record.

*Rotations.* The major initial responsibility of each student is to explore the various research possibilities available at Caltech before settling into a laboratory for their thesis research. Students are free

to rotate in any laboratory at Caltech, not just those in the biology division. First-year students should carry out a minimum of two laboratory rotations; three rotations are recommended. It is generally expected that rotations will last a full academic quarter; however, exceptions can be granted with the advance permission of the professor. Choice of laboratory should be made by July 1 of the first year except in extraordinary circumstances. This requirement can be waived by the option representative.

*Formal Classes*. During the first year of graduate studies, students are required to take a course on responsible conduct of research (Bi 252), as well as any two courses of a three-term series (Bi 250 abc) that covers the breadth of fields represented in biology at Caltech.

During each year that they are matriculated in the Ph.D. program, students are required to take Bi 251 abc (Biolunch). Students will be required to present their thesis research in Biolunch during their second and fourth years of study.

In addition to these fixed requirements, during their time at Caltech all students must take one additional 200-series or upper-division 100-series course offered by the biology division. Students may fulfill this requirement by taking three terms of Bi 250 abc.

*Teaching*. All students are to serve as teaching assistants for one quarter per year they are in residence, up through the fourth year.

*Admission to Candidacy*. The qualifying exam process that a student must complete to be admitted to candidacy is divided into two parts—an oral defense of the proposed thesis research and a written test of competency in the student's chosen area of research.

*The Oral Exam*: During winter quarter of the second year, a student is to set up a thesis proposal examining committee and prepare a proposal focused on the research project that they expect to pursue for their thesis research. The proposal is defended by the student in an oral presentation in front of the thesis proposal examining committee by the end of June. (Although it is anticipated that this exam will be completed by June of the second year, it can be delayed until August of the third year if the option representative agrees.) The examining committee comprises four faculty members, at least three of whom should hold full or joint professorial appointments in the Division of Biology. One of the members of the committee is appointed as chair. The chair of the thesis examining committee must be a Caltech faculty member other than the student's adviser. The adviser can, but need not be, a member of the examining committee. The members of the thesis proposal examining committee must certify passage of this exam. In the event that there is inadequate evidence of the capacity to do research, the student may be allowed to petition to re-take the oral exam at a later time. However, in cases where the committee deems it unlikely that the student will be able to pass a subsequent attempt, the student may be advised to leave the program. In any

event, a student cannot remain in the program beyond August of the third year without having successfully completed the requirements for admission to candidacy, except in extraordinary circumstances and with the approval of the option representative and the dean of graduate studies.

*The Written Exam*: The written qualifying examination is taken in June of the student's second year in the division. Each student chooses one of the following subjects as a major: cellular and molecular neurobiology; developmental biology; genetics; immunology; molecular biology, biochemistry, and cell biology; or systems neurobiology. The exam chair for that major designs a program of study that culminates in the written exam.

Once a student has successfully completed the oral exam and written exam, he or she can apply to be admitted to candidacy. According to Institute regulations, this application process must be completed by the end of the third year of graduate study.

*Thesis Advisory Committee Meetings*. Once a student has been formally admitted to candidacy, he or she is to pick a thesis advisory committee (TAC). This committee is often the same as the thesis proposal exam committee, but that need not be the case. The thesis adviser must be a member of the TAC. The TAC typically has five members. At least three must be professorial faculty who hold a full or joint appointment in the biology division, and at least four must be Institute professorial faculty. It is expected that students who have been admitted to candidacy will meet with the TAC once a year for the remainder of their time at Caltech. Students who fail to meet with their TAC in any one year may be deemed to not be maintaining satisfactory progress toward the Ph.D. degree and will be prevented from registering for the subsequent academic year.



*Maintaining Satisfactory Progress*. It is the policy of the biology option that a graduate student who is making satisfactory progress toward a Ph.D. degree can expect to continue as a registered student with full financial support. To be deemed as making satisfactory progress, a student is expected to fulfill the expectations listed below. In the event that satisfactory progress is not being made, a student can petition to receive the M.S. degree, for which they must have successfully completed one full year of graduate study.

Requirements for satisfactory progress include:

a. Completion of the first-year course requirements during the first year.
b. Joining a laboratory in which a student will perform thesis research before the end of the first year in residence.
c. Passing the oral and written parts of the qualifying examination and completing admission to candidacy before the start of the third year.
d. Holding a thesis advisory committee meeting in each subsequent year of studies, and having the thesis committee verify that satisfactory progress is being made.

e. Serving as a teaching assistant for one quarter of each academic year spent in residence through fourth year.
f. Completing Ph.D. studies by the end of the fifth year.

In the event that the student, option representative, and adviser are in agreement, it is possible to make exceptions to the above guidelines and remain in good standing. Extension of thesis work beyond the end of the fifth year requires that the student petition the dean of graduate studies for permission to register for the sixth year. Extensions beyond the sixth year will be allowed only in unusual circumstances. Once a student has passed admission to candidacy, the responsibility for assessing satisfactory progress lies largely with the student's thesis advisory committee. If a majority of the committee deems that a student is not making satisfactory progress, the student is at risk of being removed from the program at any time at the discretion of the option representative.

*Examination Committee*. Requirements for the Ph.D. thesis and examination are determined by the Ph.D. examination committee that is appointed by the dean of graduate studies for each degree candidate. This committee is usually the same as the thesis advisory committee, but this need not be the case. The composition of the committee must be approved by the option representative. The committee usually has five members. At least three must be professorial faculty who hold a full or joint appointment in the biology division, and at least four must be Institute professorial faculty.

*Thesis and Final Examination*. The thesis and associated publications are expected to demonstrate that the student has learned how to conceive, plan, and execute experimental and/or theoretical work that reveals new biological information. In addition, it must reveal a deep, broad, and rigorous understanding of the area of research to which the thesis is relevant.



Two weeks after copies of the thesis are provided to the examining committee, chairman, and option representative, the candidate collects the copies and comments for correction. At this time, the date for the final examination is set at the discretion of the major professor and the division chair. The final oral examination covers principally the work of the thesis, and according to Institute regulations must be held at least two weeks before the degree is conferred. Two copies of the thesis are required of the graduate for the Institute library. A third copy is required for the division library.

*Caltech-UCLA Medical Scientist Training Program (MSTP)*
A joint program between Caltech and the UCLA Medical School has been established for the granting of the the M.D./Ph.D. degree. Students do their preclinical and clinical work at UCLA, and their Ph.D. work with any member of the Caltech faculty, including the biology, chemistry, and engineering and applied science divisions.

Admission to this joint program is made through the usual UCLA MSTP process, checking a box indicating interest in the Caltech option. Students will be accepted into the joint program, funds permitting. The M.D. degree would be from UCLA and the Ph.D. would be awarded by Caltech. Ph.D. studies involving collaborations between laboratories at both institutions could lead to a joint degree with both schools being cited.

The current directors of the UCLA MSTP are Dr. Steve Smale and Dr. Kelsey Martin, and Caltech Professor Paul H. Patterson is the associate director. For more information, see http://www.medsch.ucla.edu/mstp.

*Caltech-USC M.D./Ph.D. Program*

A joint program between Caltech and the USC (Keck) Medical School has been established for the granting of the M.D./Ph.D. degree. Students do their preclinical and clinical work at USC, and their Ph.D. work with any member of the Caltech faculty.

Admission to this joint program is made through the usual USC process, checking a box indicating interest in the Caltech option. Students will be accepted into the joint program, funds permitting. The M.D. degree would be from USC and the Ph.D. would be awarded by Caltech.

The current Director of the USC M.D./Ph.D. program is Dr. Robert Chow, and Caltech Professor Paul H. Patterson is the associate director. For more information, see http://www.usc.edu/schools/medicine/education/degrees_programs/mdp/mdphd.html.

*Subject Minor*

A student majoring in another division of the Institute may, with the approval of the biology division, elect a subject minor in any of the subjects listed above under major subjects of specialization. Requirements for such a minor are determined by the faculty committee designated for each subject. A minor program in biology is also available to students of other divisions. Such a program shall consist of 45 units of upper division course work in the biology division, with each course passed with a grade of C or better. Approval of each program must be obtained from the biology graduate option representative. A student majoring in another division who elects a subject minor in biology may, if desired, arrange to have the minor designated as biology, rather than with the name of the specific minor subject.



## Chemical Engineering

*Aims and Scope of the Graduate Program*

The general objective of the graduate work in chemical engineering is to produce individuals who are exceptionally well trained to apply mathematics, the physical, chemical, and biological sciences, and engineering to the understanding of systems involving chemi-

cal reactions and transport phenomena and to the development of new processes and materials. The program also strives to develop in each student self-reliance, creativity, professional ethics, and an appreciation of the societal impact of chemical engineering and the importance of continuing intellectual growth.

*Admission*

It is expected that each applicant for graduate study in chemical engineering will have studied mathematics, physics, chemistry, biology, and chemical engineering to the extent that these subjects are covered in the required undergraduate courses at Caltech. In case the applicant's training is not equivalent, admission may be granted but the option may prescribe additional work in these subjects before recommending him or her as a candidate for a degree.

*Master's Degree*

*Course Requirements.* At least 135 units of course work must be completed in order to satisfy the Institute requirements. These units must include ChE 151 ab, ChE 152, ChE/Ch 165, 18 additional units of advanced courses in chemical engineering, 27 units of science or engineering electives, and 18 units of general electives. Finally, the M.S. requirements include at least 27 units of research, ChE 280, which represents two terms of research under the supervision of a chemical engineering faculty member or a two-term industrial research or development project performed with a member of the faculty in cooperation with professional staff at a local industrial laboratory. At least three weeks before the end of the final term of residence, a research report on the work performed under ChE 280 must be submitted to a designated member of the faculty, who will ask that it be read and approved by two members of the faculty. In addition, the fulfillment of the research report requirement must be signed off by a designated faculty member on the M.S. candidacy form and a final copy of the research report submitted to the Graduate Office no later than two weeks before the degree is to be conferred. Doctoral students who have been admitted to candidacy can use their approved candidacy report to satisfy the research report requirement of the M.S. degree.



*Degree of Doctor of Philosophy*

The work leading to the Ph.D. degree prepares students for careers in universities and in the research laboratories of industry and government. Usually the first year of graduate work is principally devoted to course work in chemical engineering and related subjects. Time is also devoted during this period to the choice and initiation of a research project. During the second year, the student is expected to spend at least half time on research, and to complete the course work and candidacy requirements.

*Admission.* Upon arrival at Caltech, each prospective Ph.D. student will meet in consultation with members of the faculty so that they may evaluate the level of the student's preparation with respect to that expected at the Ph.D. level in the areas of kinetics, thermodynamics, and transport phenomena. These consultations are held to help the student set up a course program for the first year of study. A written copy of the recommendations will be entered into each student's permanent file.

*Research Adviser.* During the first term, the faculty meets with the first-year grad students to propose topics for Ph.D. research. Following these meetings, the students are expected to meet individually with the various faculty members to discuss proposed research and generally obtain information for choosing a research adviser. At the end of the first term, each student is required to submit three faculty names, listed in order of preference. Every possible effort will be made to accommodate the student's first choice, subject to an opening in the desired research group, availability of necessary funding, etc. The final decision will be made by the chemical engineering faculty in consultation with the students.

*Oral Qualifying Exam.* Each student is required to take a subject qualifying examination at the beginning of the second quarter in residence, the purpose of which is to examine expertise in kinetics, thermodynamics, and transport phenomena. The intended level of the exam is approximately that of the corresponding undergraduate courses at Caltech. Students who fail one or more of the three subjects may be permitted, by approval of the chemical engineering faculty, to repeat the examination on the failed subject immediately after the spring term. The format and topics of the examination are distributed to the first-year students at the beginning of the fall quarter.



*Course Requirements.* Students are required to take ChE 151 ab, ChE 152, ChE/Ch 164, ChE/Ch 165, and an additional course from a designated list, selected in consultation with his/her adviser. Each student is required to complete either a subject minor, or a general program of courses outside chemical engineering consisting of at least 54 units. The choice of the 54 units is subject to certain guidelines and restrictions included in the chemical engineering graduate studies guide. The general program of courses must be approved *in advance* by the option representative. It is intended that the courses chosen should constitute some integrated program of study rather than a randomly chosen collection of courses outside chemical engineering. Within these guidelines, the only course specifically excluded is research in another option. A grade of C or better is required in any course, and a grade point average of at least 3.0 is expected. The requirements for a subject minor in any option are listed in this catalog.

*Candidacy Report/Examination.* Before the end of the spring quarter of the second year of residence, each student must submit a

written progress report on his or her research for approval by a specially constituted candidacy committee consisting of faculty members familiar with his or her general area of research. An oral examination is subsequently held by this committee to evaluate the student's ability to carry out research at the Ph.D. level. A student who fails to satisfy the candidacy requirements by the end of the second year in graduate residence will not be allowed to register in a subsequent term except by special permission of the option and the dean of graduate studies.

*Admission to Candidacy.* To be admitted to candidacy, the student must have passed the qualifying and candidacy examinations, must have had the candidacy report approved, and must have submitted an approved list of courses already taken or to be taken.

*Thesis Review Committee.* After a student passes the second-year candidacy exam, a faculty committee known as the *thesis review committee* will be appointed to review periodically the student's progress. Usually, the thesis review committee will include members of the candidacy committee, and will be appointed by the option representative based upon the student's recommendations. This committee will meet with the student before fall registration each year, either as a group or individually, to review progress, suggest improvements in research, etc. In order to expedite the review, the student should submit a two- or three-page *concise outline* of progress and of proposed future research to each member of his or her committee before the annual review meeting.

*Final Examination and Thesis.* See page 253 and the option graduate studies guide for regulations concerning final examinations and theses. A copy of the corrected thesis is to be submitted to the chemical engineering graduate secretary for the chemical engineering library.



The final examination will include the candidate's oral presentation and defense of his or her Ph.D. thesis.

All Ph.D. students are required to perform a minimum of 18 term-hours of graduate teaching assistantship (GTA) duties during their studies. GTA duties will normally be assigned after the first year in residence. Serving as TA for classes outside chemical engineering may be allowed at the discretion of the option representative.

*Subject Minor*

Graduate students electing a subject minor in chemical engineering must complete 54 units of graduate courses in chemical engineering that are approved by the chemical engineering faculty. The 54 units will consist of no more than 18 units from ChE 101, 103 abc, 105, and 110 ab, and at least 36 units from ChE 151 ab, ChE 152, ChE/Ch 164, ChE/Ch 165, and a list of chemical engineering courses provided by the option representative. A 3.0 GPA is required for the courses taken.

*Graduate Studies Adviser, Option Representative, and Chemical Engineering Graduate Studies Committee.* During graduate studies, students will interact with several members of the chemical engineering faculty. The most intensive interaction will be with the research adviser, who will advise on all aspects of Ph.D. research and course work and will approve various formal requirements. Each student will be assigned a graduate mentor to provide additional perspective on the student's progress and on any problems that may arise. The student will also interact with the members of the thesis review committee, as discussed earlier. In addition, they will interact with the option representative and the graduate studies adviser. During the first year, the graduate studies adviser will advise the students about choice of research adviser, choice of courses, and Ph.D. qualifying exams. The option representative is responsible for GRA (graduate research assistantship) or GTA (graduate teaching assistantship) assignments, beyond the first year, and for approval of the Candidacy and Thesis Review Committees and other formal requirements for the M.S. and Ph.D. degrees. Students may contact either of these two faculty members regarding any questions or problems. In a case where the relationship between a student and his or her research adviser becomes strained and the student desires advice or help from other faculty, he or she should consult with the Chemical Engineering Graduate Studies Committee, consisting of the option representative, the graduate studies adviser, and the option executive officer.

*Additional Information.* Additional information about graduate study requirements and procedures is provided in the chemical engineering graduate studies guide, distributed annually to first-year chemical engineering graduate students.



## Chemistry

*Aims and Scope of the Graduate Program*

The graduate program in chemistry emphasizes research. This emphasis reflects the Institute's traditional leadership in chemical research and the conviction that has permeated the Division of Chemistry and Chemical Engineering from its founding, that participation in original research is the best way to awaken, develop, and give direction to creativity.

Soon after a new graduate student arrives in the laboratories, he or she attends a series of orientation seminars that introduce students to the active research interests of the staff. Students then talk in detail with each of several staff members whose fields attract them, eventually settle upon the outlines of a research problem that interests them, and begin research upon it early in the first year. Students can elect to do research that crosses the boundaries of traditionally separate areas of chemistry, for in this relatively compact division, they are encouraged to go where their scientific curiosity drives them. A thesis that involves more than one adviser

is not uncommon, and interdisciplinary programs with biology, physics, geology, chemical engineering, and environmental science and engineering science are open and encouraged.

An extensive program of seminars will enable students to hear of and discuss notable work in chemical physics, organic chemistry, inorganic chemistry and electrochemistry, organometallic chemistry, and biochemistry and molecular biophysics. Graduate students are also encouraged to attend seminars in other divisions.

*Course Program*

A student is required to complete at least five courses, each being nine units or more, in science or engineering. At least one course must be in a field substantially outside the research area of the student. Courses may be either inside or outside the chemistry option, must be numbered 100 or greater, and must be taken on a letter-grade basis unless the course is offered with only the pass/fail option. A grade of B or better is required for credit. The student should discuss with his or her adviser which courses best serve his or her individual needs. The program of courses must be approved by the research adviser and the Chemistry Graduate Study Committee. Alternatively, a student may complete a subject minor in another option, the course requirements being set by that option.

*Master's Degree*

Students are not ordinarily admitted to graduate work leading to an M.S. degree. Under special circumstances, and with prior approval of the Graduate Study Committee, a master's degree can be obtained. All master's programs for the degree in chemistry must include at least 40 units of chemical research and at least 30 units of advanced courses in science. The remaining electives may be satisfied by advanced work in any area of mathematics, science, engineering, or the humanities, or by chemical research. Two copies of a satisfactory thesis describing this research, including a one-page digest or summary of the main results obtained, must be submitted to the divisional graduate secretary at least 10 days before the degree is to be conferred. In addition, the fulfillment of the thesis requirement must be signed off by a designated faculty member on the M.S. candidacy form and a final copy of the thesis submitted to the Graduate Office no later than two weeks before the degree is to be conferred. The copies of the thesis should be prepared according to the directions formulated by the dean of graduate studies and should be accompanied by a statement approving the thesis, signed by the staff member directing the research and by the chair of the Chemistry Graduate Study Committee.

*Degree of Doctor of Philosophy*

*Candidacy.* To be recommended for candidacy for the doctor's degree in chemistry, in addition to demonstrating an understanding and knowledge of the fundamentals of chemistry, a student must give satisfactory evidence of proficiency at a high level in the primary field of interest, as approved by the division. This is accomplished by an oral candidacy examination, which must be held during or before the fifth term of graduate residence (excluding summer terms). The candidacy committee shall consist of three members of the chemistry faculty. The committee should be considered as a resource for the student for the remainder of his or her studies. At the candidacy examination, a student is asked to demonstrate scientific and professional competence and promise by discussing a research report and propositions as described below.

The research report should describe progress and accomplishments to date and plans for future research. Two original research propositions, or brief scientific theses, must accompany the report, and at least one must be well removed from the student's field of research. These propositions should reflect his or her breadth of familiarity with the literature, originality, and ability to pose and analyze suitable scientific research problems. The research report and propositions must be in the hands of the examining committee one week before the examination.

The result of the candidacy examination may be either (a) pass, (b) fail, or (c) conditional. Conditional status is granted when the committee decides that deficiencies in a student's research report, propositions, or overall progress can be remedied in a specific and relatively brief period of time. In order to change conditional to pass status, the student must correct the indicated deficiencies or in some cases schedule a new examination the following term. He or she must be admitted to candidacy at least three terms before the final oral examination. A student cannot continue in graduate work in chemistry (nor can financial assistance be continued) past the end of the sixth term of residence without being admitted to candidacy, except by petitioning the division for special permission. This permission, to be requested by a petition submitted to the Graduate Study Committee stating a proposed timetable for correction of deficiencies, must be submitted before registration for each subsequent term (including the summer following the sixth term of residence) until admission to candidacy is achieved.



*Language Requirement.* There is no formal foreign language requirement for the Ph.D. in chemistry. However, the division believes strongly in the professional importance to chemists of a knowledge of foreign languages and encourages their study prior to graduate work or while in graduate school.

*Thesis Research Progress.* Before the thirteenth term of graduate residence (excluding summer terms), the student will be expected to demonstrate satisfactory progress in the course of thesis

research. To this end, an informal meeting with the Ph.D. thesis committee will be held, at which time the student will present an oral summary of research completed to date as well as an outline of future research plans. The thesis committee will generally consist of the original candidacy committee plus an additional member of the faculty. Following the presentation, an appropriate timetable for completion of the degree requirements will be discussed and agreed upon. If the student has not progressed sufficiently, completion of the Ph.D. may be considered inappropriate.

*Length of Graduate Residence.* Any graduate student who anticipates a need to register for a 16th academic term must request a meeting of his or her thesis committee and present a petition for permission to register that includes a plan of action for the period of the requested registration and a specific date for the completion of the degree requirements. This petition must be approved by the chair of the Chemistry Graduate Study Committee and, in cases where financial support is an issue, also by the executive officer or division chair, before it is forwarded to the dean of graduate studies. Financial support of graduate students who are required to petition to register will not normally be provided through teaching assistantships. Failure to complete the degree requirements by the date specified in the petition would require the entire approval process to be repeated.

*Thesis and Final Examination.* The final examination will consist in part of the oral presentation and defense of a brief résumé of the student's research and in part of the defense of a set of propositions he or she prepares. Three original research propositions are required. No more than *one* of these may be a carryover from the candidacy examination, and *at least one* must be *well removed* from the field of research. Each proposition shall be stated explicitly and the argument presented in writing with adequate documentation. The propositions should display originality, breadth of interest, and soundness of training; a student will be judged on the selection and formulation of the propositions as well as on the defense of them. Formulating a set of propositions should begin early in the course of graduate study.



To emphasize the importance of these propositions, there will be a separate examination on the three propositions by the Ph.D. thesis committee. This examination on the propositions is normally taken after the thesis research progress meeting, but must be held before the end of the fifth year of residence, and not less than 10 weeks in advance of the final doctoral examination. A copy of the propositions, along with suitable abstracts, must be submitted to the examining committee and to the division graduate secretary not less than two weeks before the propositions examination. These propositions must be acceptable to the committee before the final doctoral examination can be scheduled.

A copy of the thesis must be submitted to each member of the thesis committee not less than two weeks before the final doctoral

examination. A copy of the thesis should also be submitted to the Graduate Office for proofreading three weeks prior to the final doctoral examination. One reproduced copy of the thesis, corrected after proofreading, is to be submitted to the division graduate secretary for the divisional library. Two final copies (one on Permalife paper) are to be submitted to the Graduate Office.

*Subject Minor*
Graduate students in other options taking chemistry as a subject minor will be assigned a faculty adviser in chemistry by the Chemistry Graduate Study Committee. In consultation with this adviser, the student will work out an integrated program of courses, including at least 45 units of formal course work at the 100 level or above. This program must be approved by the Chemistry Graduate Study Committee, and a grade of C or better in each course in the approved program will be required.

## Civil Engineering

*Preparation for the Graduate Program*
Students who have not specialized in civil engineering as undergraduates, as well as those who have, may be admitted for graduate study. As preparation for advanced study and research, a good four-year undergraduate program in mathematics and the sciences may be substituted for a four-year undergraduate engineering course, with the approval of the faculty. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty.



*Master's Degree*
For the M.S. degree a minimum of 138 units of academic credit for courses numbered 100 or above is required. The program must include three units of CE 130 abc and at least 81 units of graduate-level courses in CE and AM. Students who have not had ACM 100 abc or its equivalent will be required to include ACM 100 in their program. The M.S. program must be approved by the student's adviser and the option representative for civil engineering. Ordinarily, the degree program will be completed in one academic year.

Students admitted for study toward a master's degree but interested in pursuing subsequent study toward a Ph.D. degree should also read the section below concerning this degree.

*Degree of Civil Engineer*
Greater specialization is provided by work for the engineer's degree than for the master's. The candidate for this degree is allowed wide latitude in selecting his or her program of study, and is encouraged to elect related course work of advanced nature in the basic sciences. The degree of Civil Engineer is considered to

be a terminal degree for the student who desires advanced training more highly specialized and with less emphasis on research than is appropriate to the degree of Doctor of Philosophy. However, research leading to a thesis is required for both degrees. The student should refer to Institute requirements for the engineer's degree.

*Degree of Doctor of Philosophy*

Study and research programs for the Ph.D. degree are individually planned to fit the interests and background of the student. A comprehensive research project leading to a thesis is required. Examples of areas of research are described in section two.

*Advising and Thesis Supervision.* A counseling committee of three faculty members is appointed for each student upon his or her admission to work toward a Ph.D. degree in civil engineering, in order to advise the student on a suitable course program. One committee member acts as committee chair and interim adviser until this responsibility is assumed by the thesis adviser. This committee must meet during the first and third terms of each year of Ph.D. study.

The thesis adviser and thesis advisory committee provide the majority of mentoring to the student. In addition, the option representative and other members of the faculty are always available to provide advice and mentoring on any aspect of research, progress toward the Ph.D., future careers, and other aspects of life in graduate school and as a professional scientist or engineer.

*Admission to or Continuation in Ph.D. Status.* Newly admitted students, those continuing to study toward the Ph.D. degree in civil engineering, and other graduate students wishing to become eligible for study toward this degree, must make satisfactory progress in their academic studies each year, as judged by a special joint faculty committee.



*Admission to Candidacy.* To be recommended for candidacy for the Ph.D. degree in civil engineering, the student must, in addition to meeting the general Institute requirements, do the following:

- Complete 27 units of research.
- Complete at least 108 units of advanced courses, arranged in conference with his or her adviser and approved by the faculty in civil engineering.
- Pass with a grade of at least C an additional 27 units of course work in advanced mathematics, such as AM 125 abc or a substitute acceptable to the faculty in civil engineering.
- Pass a two-part oral candidacy examination in the second academic year of graduate residence at the Institute.

*Thesis and Final Examination.* A final oral examination will be given after the thesis has been formally completed. Copies of the completed thesis must be provided to the examining committee at least two weeks prior to the examination. This thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in his or her specialized field of research.

*Subject Minor*
A student majoring in another branch of engineering, or in another division of the Institute, may elect civil engineering as a subject minor, with the approval of the faculty in civil engineering and the faculty in the student's major field. The group of courses shall differ markedly from the major subject of study or research, and shall consist of at least 54 units of courses approved by the faculty in civil engineering.

## Computation and Neural Systems

*Aims and Scope of the Graduate Program*
An integrated approach to graduate study combining computation and neural systems is organized jointly by the Division of Biology, the Division of Engineering and Applied Science, and the Division of the Humanities and Social Sciences. This curriculum is designed to promote a broad knowledge of aspects of molecular, cellular, systems and cognitive neuroscience, computational biology and computational neuroscience, information and learning theory; emergent or collective systems; and computer science and electrical engineering; in conjunction with an appropriate depth of knowledge in the particular field of the thesis research. For more details, see http://www.cns.caltech.edu.

*Admission*
Ideal applicants will have a Bachelor of Science degree or equivalent with a strong quantitative background and some facility with computer programming. They will have shown an interest in understanding the brain and/or in autonomous intelligent systems. All applicants are strongly encouraged to submit their Graduate Record Examination (GRE) verbal and quantitative scores.



*Advisory Committee and TA Requirement*
An advisory committee of three CNS faculty members is constituted for each student by the CNS admissions committee upon admission to the program. The faculty in whose lab the student is staying first chairs this committee. The advisory committee meets with the student when he or she arrives, guides and approves first-year course choices, and answers questions and offers advice about the program and the way of life in CNS. The CNS faculty are available to students during the year for formal and/or informal discussions.

It is expected that each graduate student will serve as a teaching assistant in one or two CNS courses during his or her residency at Caltech as part of the Ph.D. graduation requirement.

*Master's Program*
Only students who expect to pursue the Ph.D. degree will be admitted to the option. The master's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the

Institute requirements for a master's degree, satisfying the option breadth requirements (see following section), the completion of a master's thesis, and receiving from a candidacy examination oral committee a recommendation for awarding the degree.

*Laboratory Rotations*
Mandatory rotations through research groups (labs) provide a unique opportunity for the student to experience the CNS culture. To broaden the student's knowledge and to provide familiarity with different techniques and ways of thinking or doing research, each student should carry out three 12-week laboratory rotations (one per term) during the first year, and should engage in research. During each rotation, the student is expected to take part in the life and routine of the lab by attending lab meetings; participating in research projects and discussions with members of the lab; and meeting monthly with the faculty of that lab to discuss science.

*Course Requirements*
Six nine-unit courses are required during the first year: CNS/Bi/Ph/CS 187, either Bi 9 or equivalent, or Bi/CNS 150, a neurobiology or modeling course, a math course, and two other CNS, Bi, EE, ACM, or Ph courses (for example, a schedule of CNS/Bi/Psy 120, CNS/Bi/EE 186, CNS 187, Bi/CNS 150, and CS/CNS/EE 156 satisfies this requirement). CNS students are required to take two additional classes: the one-unit survey course CNS 100, and the four-unit course Bi 252. These eight courses must be taken for letter grades. Students are free to take additional classes, and a research adviser may require that a student take a specific, complementary course as a requirement for joining his or her lab.



*Candidacy*
Five faculty, including the three faculty in whose labs rotations have been done, should be on the student's candidacy exam committee. At the end of the first year, the student is expected to decide on a research group and begin work there. The first summer is thus expected to be spent entirely on research in that lab. Advancing to candidacy requires passing two tests: the general knowledge exam, and the research and candidacy exam. These exams are supervised by the CNS option representative.

The general knowledge exam satisfies the breadth requirement. A list of about 100 questions, grouped by category, is available at http://www.cns.caltech.edu, providing a clear idea of the scope of knowledge that each student is expected to know well. Students are encouraged to organize working and discussion groups to prepare for this exam; the format and implementation of such a system, however, is left to the students.

This is an oral exam, with the five faculty (including the heads of the student's three rotation labs and two others chosen for

"breadth," of whom one can be from outside Caltech). It should be scheduled by the student (who contacts the committee members) to take place during the last six weeks of the third term of year one. For the exam, the student must answer questions (from more than one category) taken from the list, which is modified each year. (The exam can be retaken after three months.)

The research and candidacy exam satisfies the depth requirement. During year two, the student is expected to produce a piece of work of a quality sufficient to be presented at a professional meeting. (The objective of this description is to offer a way to calibrate the level of expected research achievement and involvement. Professional acceptance of the abstract or paper is not a requirement for passing candidacy.) This work is presented in an oral exam in spring term of year two, before the same exam committee (if possible) that conducted part one of the exam. The exam focuses exclusively on research (accomplished and/or planned). During year two, the student may take other courses, as needed, but is expected to present a high standard (quality, originality) of research at the time of this second part of the candidacy exam.

*Subject Minor.* Students majoring in other fields may take a subject minor in CNS, provided the program is supervised by a CNS adviser, is approved by the CNS option representative, and consists of 45 units, including Bi/CNS 150, CNS/Bi/Ph/CS 187, Bi 252, and other CNS cross-listed classes. A subject minor is not required for the Ph.D. degree in CNS.

## Computational Science and Engineering



*Aims and Scope of the Minor*

Computational Science and Engineering (CSE) may be pursued as a subject minor by graduate students who are pursuing Ph.D. degrees in any option. The CSE minor is intended to supplement one of Caltech's graduate degrees and is designed for students who wish to broaden their knowledge of CSE beyond their major field of study. The CSE minor is also intended to recognize graduate students' interest in and dedication to CSE as demonstrated by the successful completion of a program of study in the field. Completion of the CSE minor program of study will be recognized on the Ph.D. diploma by the statement, "…and by additional studies constituting a minor in Computational Science and Engineering."

*Requirements*

To receive the CSE minor, graduate students must fulfill the following requirements.

- 18 units (two terms) from the following list: ACM 106 abc, ACM 113, ACM/CS 114, ACM/ESE 118, ACM 126 ab, ACM 210 abc, ACM 216.

- 18 units (two terms) from the following list: CS/EE/Ma 129 abc, CS 138 abc, CS 139 abc, CS 150, CS/CNS/EE 156 a.
- 9 units (one term) from the list: Ae/AM/CE/ME 214 abc, Ae/AM/ME 232 ab, Ay 199, Ch 121 ab, GE 263, Ph/CS 219 abc.

All courses to be applied toward the CSE minor requirements must be taken on a graded basis, and students must obtain a grade of B or higher in all courses. Courses that are used to satisfy the CSE minor cannot be used to satisfy course requirements in the major options unless absolutely required by the option. Courses taken as part of the CSE minor are counted toward the total number of units required for the completion of the Ph.D. degree.

*CSE Minor Administration*
The CSE minor is administered by an oversight committee consisting of three faculty members reporting to the chair of the engineering and applied science division. In consultation with their advisers and, if needed, with the CSE Oversight Committee, students formulate a program of approved courses individually tailored to each student's background and needs, with the objective that the student achieve a level of competence in specific subjects relevant to CSE. Students must petition the CSE Oversight Committee for approval of their program of study. Upon completion of the program of study, the CSE Oversight Committee will verify that the CSE minor requirements have been fulfilled.

## Computer Science



*Aims and Scope of the Graduate Program*
Graduate study in computer science within the Computing & Mathematical Sciences department is oriented principally toward Ph.D. research. The course work and thesis requirements for the M.S. degree are a required part of the Ph.D. program. There is no admission to the M.S. program as the degree objective.

Students entering the graduate program with an M.S. degree from another school may transfer credit for course work as appropriate. A student may petition the option representative to have a prior M.S. thesis or equivalent accepted in lieu of a Caltech M.S. thesis; no Caltech M.S. will be granted in this case.

The Ph.D. program requires a minimum of three academic years of residence. The M.S. should be completed within the first two years.

Students must maintain high academic standards during their graduate residence. A student's Ph.D. research must exhibit originality in the formulation, analysis, and solution of a problem that is significant to the field of study. The option representative and executive officers are available to discuss concerns regarding academic progress.

*Master's Degree*

There are five requirements to fulfill for the M.S. in computer science:

- *Total units.* Completion of a minimum of 135 units of courses numbered 100 or greater, including M.S. thesis research (CS 180). The student will consult with the adviser to ensure balance in the course work.
- *Advanced courses in computer science.* Completion of a minimum of 54 units of CS courses numbered 100 or greater in addition to units earned for reading, research, projects, and the M.S. thesis.
- *Units outside computer science.* Completion of a minimum of 27 units outside computer science. Courses jointly listed with computer science cannot be used to fulfill this requirement.
- *Breadth.* Toward the end of the first year, all incoming students must successfully pass a diagnostics exam administered by the faculty. Its purpose is to ensure a solid and broad knowledge in computer science, and/or to direct the students to necessary courses and reading.
- *M.S. thesis.* At the end of the second year, students must have completed a minimum of 45 units of CS 180, had their M.S. thesis approved by a computer science faculty member, obtained the signature of a designated computer science faculty member on the M.S. candidacy form, and submitted a copy of the M.S. thesis to the Graduate Office no later than two weeks before the degree is to be conferred.

*Degree of Doctor of Philosophy*



*Candidacy.* To be admitted to candidacy, a student must have completed the M.S. program, have entered upon a course of research approved by his or her thesis adviser, and have passed a candidacy oral examination. The candidacy oral examination will be administered by a committee that consists of four faculty, is approved by the option representative, and is chaired by the adviser. The examination will ascertain the student's breadth and depth of preparation for research in the chosen area. The examination should be taken within the first three years.

*Advising and Thesis Supervision.* In order to facilitate close supervision and a highly research-oriented environment, each student is admitted directly to an adviser and research group. A course of study is determined in consultation with the adviser. Occasionally students will be admitted into more than one group. Changes in affiliation may occur with the common consent of the student and the new adviser.

Students meet regularly with their adviser throughout their time at Caltech, and are encouraged to do the same with other members of the faculty.

*Thesis and Final Examination.* A final oral examination will be scheduled and given after the Ph.D. thesis has been submitted for review to the student's adviser and thesis committee; the latter consists of at least four faculty approved by the option representative, and is chaired by the adviser. The thesis examination is a defense of the thesis research and a test of the candidate's knowledge in his or her specialized fields.

*Subject Minor in Computer Science*

A subject minor is not required for the Ph.D. degree in computer science. However, students majoring in other fields may take a subject minor in computer science, provided the program is supervised by a computer science faculty adviser, is approved by the computer science option representative, and consists of 45 units sufficiently removed from the student's major program of study.

*Subject Minor in Applied Computation*

The subject minor in applied computation is administered jointly by the applied and computational mathematics and computer science options, and is open to graduate students in all options. This minor emphasizes the mathematical, numerical, algorithmic, and programming methods underlying the application of computation—particularly parallel and concurrent computation—to research in science and engineering.

The requirements are listed under Applied and Computational Mathematics.

## Control and Dynamical Systems

*Aims and Scope of the Graduate Program*



The option in control and dynamical systems (CDS) is open to students with an undergraduate degree in engineering, mathematics, or science. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty. In some cases the student may be required to make up undergraduate deficiencies in engineering science courses.

The CDS option, as part of the Computing & Mathematical Sciences department, emphasizes the interdisciplinary nature of modern theory of dynamical systems and control. The curriculum is designed to promote a broad knowledge of mathematical and experimental techniques in dynamical systems theory and control. In addition to taking courses in the CDS option, students must select a focus area (see below).

*Master's Degree*

Students will be admitted to the option who expect to pursue the Ph.D. degree. The master's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for a master's degree, satisfying the focus requirements, and receiving a recommendation for awarding of the degree from the candidacy oral examination committee.

*Degree of Doctor of Philosophy*

Institute requirements for the Ph.D. degree are described in the section on degree requirements. Approximately two years of course work are required, and two or more years are usually needed for preparation of the dissertation.

*Admission to Candidacy.* To be recommended for candidacy for the Ph.D. degree in control and dynamical systems, the student must, in addition to meeting the general Institute requirements, do the following:

- Complete the following courses: ACM/EE 116; CDS 140 a or Ma 147 ab; CDS 201 or Ma 108 ab; CDS 202 or Ma 109 ab.
- Complete the focus requirement, consisting of at least 27 units in a particular area outside of CDS. Courses taken to satisfy the focus must represent a coherent program of advanced study in the chosen area. Possible areas include biological systems, computer science, environmental science, fluid dynamics, information and communications, neworking, robotics, and space systems. The program of study must be approved by the student's counseling committee and the option representative.
- Complete an additional 45 units in CDS or other advanced courses in systems theory, dynamical systems, and/or applied mathematics.
- Prepare a research progress report.
- Pass an oral examination on the major subjects. The oral examination is normally taken before the end of the second year of graduate academic residence at the Institute.

*Advising and Thesis Supervision.* Upon admission, each student is assigned an adviser in the option and a committee of three members, chaired by the adviser, which will approve the initial course of study by the student. A qualifying exam given during the first year of study will be used to evaluate the student's preparation for continued study.

The adviser will be replaced by a research adviser, and the initial committee replaced by a (possibly identical) candidacy committee when the direction of specialization is determined, not later than the beginning of the second year. The candidacy exam is normally taken toward the end of the second year. The candidacy committee will be the judge of the completion of the engineering focus requirement, necessary before advancement to candidacy. The student's candidacy committee may be reconstituted as the thesis committee after the candidacy exam has been successfully completed.

At the early stages of thesis preparation, the student's thesis committee will meet as needed, but at least yearly, to advise the student of his or her progress and to deal with any problems that might have arisen.

A final oral examination will be given after the thesis has been

formally completed. The thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in the specialized field of research. Normally this defense will consist of a one-hour public lecture followed by an examination of the thesis by the thesis committee.

*Subject Minor*
A student majoring in another option at the Institute may elect a subject minor in control and dynamical systems. He or she must obtain approval from the CDS faculty of a course of study containing at least 54 units of advanced courses with a CDS listing.

## Electrical Engineering

*Aims and Scope of the Graduate Program*
Award of the Bachelor of Science degree may be followed by graduate study leading to the Master of Science degree in electrical engineering, and the more advanced degrees of Electrical Engineer or Doctor of Philosophy. Because admission to graduate studies in electrical engineering at Caltech is extremely competitive, the Admissions Committee attempts to select those applicants it judges both best qualified and best suited for the graduate program. Applicants should submit Graduate Record Examination scores.

*Master's Degree*
Normally, the master's degree in electrical engineering is completed in one academic year. The principal criteria for evaluating applicants for the MSEE are the excellence of their preparation for the math- and physics-oriented nature of Caltech's graduate courses, and the judgment of the Admissions Committee on their ability to successfully pursue and benefit from the course program. The Institute does not normally admit an applicant to the master's degree in a field in which the applicant already has a master's degree from another U.S. institution. Financial aid is seldom offered to those who intend to complete their graduate work with a master's degree. A joint B.S./M.S. degree is not available in electrical engineering.

135 units (100 or above except some specially petitioned humanities courses) are required as approved by the electrical engineering graduate student adviser. No more than 30 units of pass/fail grades may be counted toward this requirement. Units toward this are not transferable from other schools. At least 54 units of EE letter-graded courses (courses listed or cross-listed as EE) labeled 100 or above and not counting EE 191 or EE 291 are required. EE 105 abc, Electrical Engineering Seminar, is also required. Students are urged to consider including a humanities course in the remaining free electives.

Students who have been admitted to the M.S.-only program must reapply if they are interested in the Ph.D. program.

*Degree of Electrical Engineer*
The engineer's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for an engineer's degree and receiving a recommendation for its awarding from the candidacy oral examination committee.

*Degree of Doctor of Philosophy*
As a rule, applicants who wish to undertake research work leading to a degree of Doctor of Philosophy in electrical engineering are admitted initially only for the MSEE. They are, however, evaluated according to additional criteria, the most important of which is the applicant's interest in and potential for research in one of the areas described below. The statement of purpose required as part of the application should clearly address this match. Considerable weight is also given to the opinions expressed in the applicant's letters of recommendation.

During the Ph.D. applicant's master's degree year, evaluation continues. It is based in part on performance in courses and in part on a one-hour oral presentation scheduled early in the second quarter. As the year progresses, the electrical engineering faculty get to know the student, and the student makes contact with the professor in his or her area of research interest. Upon acceptance into a research group, the student begins research work and defers receiving the master's degree until formal admission into the Ph.D. program. Before the end of his or her second academic year of graduate study, the student normally takes the Ph.D. qualifying oral examination. This must, however, be done no later than the end of the third academic year.

Ph.D. applicants who already hold a master's degree in electrical engineering from another U.S. institution may be admitted directly to the Ph.D. program, but must provide sufficient information to obtain advance acceptance into a research group.



Financial aid available to a Ph.D. applicant includes teaching assistantships and fellowships. TA duties consist of grading papers or lab instruction but not classroom lecturing. A fellowship may be supplemented by a teaching assistantship, and either or both include a full tuition scholarship. Tuition scholarships alone are not available. If financial aid is not requested, or if the box on the application form labeled "willing to come without aid" is checked, information on the source of funds for each year of intended graduate study must be included.

*Candidacy.* To be recommended for candidacy for the doctor's degree, the applicant must satisfy the following requirements (and pass the Ph.D. qualifying oral examination) no later than the end of the third academic year:

- Complete 18 units of research in his or her field of interest.
- Obtain approval of a course of study consisting of at least 135 units of advanced courses in electrical engineering or

the related subjects listed under the master's degree. Only up to 27 units in research (e.g., EE 291) may be counted in this total. No more than 30 units of pass/fail grades may be counted toward this requirement. The courses taken to satisfy the math requirement below and courses taken to fulfill the Master of Science degree requirement may be included to satisfy this requirement. Units toward this requirement are not transferable from other schools.

- Pass 27 units of mathematics courses, as approved by the student's research adviser, with letter grade no lower than C.
- Pass a qualifying oral examination covering broadly the major field. Students are strongly encouraged to do this before the end of the second year of residency.

*Ph.D. Committee.* The Ph.D. qualifying oral exam and the final defense exam are conducted by committees that are set up by the student and approved by the option representative. Members of these Ph.D. committees also serve as second or backup mentors in cases where such additional advising and problem solving are appropriate.

*Thesis and Final Examination.* The candidate is required to take a final oral examination covering the doctoral thesis and its significance in and its relation to his or her major field. This final examination will be given not less than two weeks after the doctoral thesis has been presented in final form, and before its approval. This examination must be taken at least four weeks before the commencement at which the degree is to be granted.

*Advising and Thesis Supervision.* Periodic meetings between the advising faculty and the graduate student are an integral part of the Ph.D. program. These meetings should be at sufficiently frequent intervals, as determined by the student and adviser. Students are also encouraged to meet with other members of the Ph.D. committee, the option representative, the executive officer, or Caltech's ombudsperson to discuss problems relating to satisfactory progress.



*Subject Minor*

A student majoring in another option at the Institute may elect a subject minor in electrical engineering. He or she must obtain approval from the electrical engineering faculty of a course of study containing at least 45 units (over the 100 level) of advanced courses with an EE listing (excluding EE 191 and 291). At least 36 of these should be for letter grades no lower than C. Freshman classes cannot be counted toward this.

## Environmental Science and Engineering

*Aims and Scope of the Graduate Program*

The interdisciplinary problems posed by natural and human-induced changes in the earth's environment are among the most interesting, difficult, and important facing today's scientists and

engineers. The environmental science and engineering option is an interdivisional program of study by biologists, chemists, physicists, earth scientists, and engineers to investigate the functioning of and interactions among the atmosphere, hydrosphere, biosphere, and lithosphere. The ESE option is administered by the Division of Chemistry and Chemical Engineering, the Division of Engineering and Applied Science, and the Division of Geological and Planetary Sciences and promotes both broad knowledge of natural and engineered environmental systems and a detailed understanding of the application of basic science to environmental issues.

*Admission*
Applicants for admission to the option should have undergraduate preparation in science, engineering, or mathematics. Admission is limited to students intending to pursue the Ph.D. degree. Applicants are required to submit Graduate Record Examination (GRE) scores for the aptitude tests. Applicants from non-English-speaking nations are required to submit Test of English As a Foreign Language (TOEFL) scores.

*Master's Degree*
Students enrolled in the Ph.D. program may be awarded a master's degree if they have satisfied the basic Institute requirement of 135 units of work in courses numbered 100 or higher. These courses must include those specifically required in the ESE Ph.D. program and satisfy the ESE core requirement.

*Advising*
An academic adviser is appointed for each incoming student to assist in design of his or her academic program. The research adviser will be chosen by mutual agreement of the student and adviser before the end of the student's third term of graduate study. The thesis advisory committee (TAC), consisting of four faculty including the research adviser, will be constituted and will meet with the student soon after the student successfully completes the Ph.D. qualifying examination, and should thereafter meet with the student yearly. Committee membership may change with the student's research interests. TAC members will generally serve to approve the student's advancement to candidacy and as the examining committee for the final thesis defense.



*Degree of Doctor of Philosophy*
For the Ph.D. degree, the student must (1) satisfy the course requirements, (2) pass the qualifying examination, (3) advance to candidacy, and (4) complete a thesis and successfully defend it in a final oral examination.

*Course Requirements.* The program of courses for the Ph.D. degree should be designed to educate students in the application of the basic sciences to environmental problems and to prepare them

for their research. During their first year, students, in consultation with their academic advisers, must design a program of graduate study that includes a minimum of 135 units of graduate work to be completed before the end of their third year. The Ph.D. program must include three units of ESE 150 abc and three units of ESE 101. Courses in mathematical physics, such as Ge 108, and in applied statistics and data analysis, such as ACM/ESE 118, are required for students lacking this preparation. Note that advanced courses in biology with a strong quantitative component may be substituted in appropriate cases upon petition by the student. Students are further required to take 18 units in each of the three core areas—environmental chemistry, biology, and physics—for a total of 54 units in the core courses. Courses satisfying the core requirements are

- *Environmental Biology:* ESE/Ge 148 c, ESE/Bi 166, Ge/ESE 170;
- *Environmental Chemistry:* ESE 142, ESE/Ge/Ch 171, ESE/Ch/Ge 175 a;
- *Environmental Physics:* ESE/Ge 148 ab.

In cases of unusual preparation, students may petition to substitute an advanced elective course for a core course, but the substituted courses must be in the same area as the courses replaced. The remaining units required are to be fulfilled by taking additional core courses (not used to satisfy the core requirement) or elective courses in ESE or related disciplines. In recognition that solutions to environmental problems are limited not only by technical but also by social, political, and economic issues, students are encouraged to include relevant courses in the social sciences in their program of study. For recommended elective courses, see http://www.ese.caltech.edu/courses/electives.html. Not more than 42 units may be in reading and/or research (ESE 100, 200, 300) courses (these units are in addition to the required six units of ESE 101 and ESE 150 abc). Of these reading and/or research units, not more than 27 units may be taken during the first year of graduate study. Exceptions may be granted by petition. Courses may be taken at the Scripps Institution of Oceanography under the exchange arrangement described on page 246.



*Ph.D. Qualifying Examination.* The Ph.D. qualifying examination must be taken during the first term of the student's second year of residency. This examination consists principally of oral and written defense of two research propositions, supplemented by a written description of one of them. Written abstracts must be submitted for both propositions. Fundamental questions derived from the ESE core courses may also be included in the qualifying examination. Students are encouraged to consult with others concerning their ideas on propositions, but the material submitted must be the work of the student. There must be a different faculty member associated with each of the two propositions. It is expected

that the student's research adviser will supervise the proposition for which the student prepares the written description. This written description will generally be in the form of a proposal, but the student may submit a research paper instead. In preparation for the qualifying examination, students are encouraged to register for nine units of research (ESE 100) in their second and third terms of residence.

*Advancement to Candidacy.* Students are expected to advance to candidacy before the end of the first term of their third year of residency.

*Thesis and Final Examination.* Copies of the completed thesis must be provided to the examining committee two weeks before the examination. The final oral examination focuses on the work of the thesis and, according to Institute regulations, must be held at least two weeks before the degree is conferred.

*Subject Minor*
Students majoring in another option at the Institute may elect a subject minor in environmental science and engineering. They must obtain approval from the ESE option representative for a course of study containing at least 45 units of advanced ESE courses.

## Geological and Planetary Sciences

*Aims and Scope of the Graduate Program*
Students in the Division of Geological and Planetary Sciences study the earth and planets to understand their origin, constitution, and development, and the effect of the resulting physical and chemical characteristics on the history of life, on the environment, and on humanity. Broad training in the fundamental sciences enriched by more specialized course work within the division forms the basis of the educational program. Students are encouraged to work with complex and often incomplete data sets, to undertake research in natural settings such as in the field or at sea, and to use the many modern laboratory facilities available within the division. Programs of study and research are pursued in environmental science and engineering, geology, geobiology, geochemistry, geophysics, and planetary science. The curriculum is flexible so that students with diverse degrees in science and engineering may carry out graduate work within the division. Interdisciplinary studies are encouraged and students may carry out academic and research programs within and between different divisions. The objective is to train students for future employment in academic research, government, and industry.



*Admission and Entrance Procedures*
Only students who intend to work full-time toward the Doctor of Philosophy (Ph.D.) degree are admitted. The admission process follows Institute regulations. Applicants are required to submit Graduate Record Examination (GRE) scores for the general test.

Individual option requirements for GRE subject tests are specified below:

Environmental Science and Engineering—No.
Geobiology—Submit the scores for any subject test.
Geochemistry—Strongly recommended but not required.
Geology—No.
Geophysics—No.
Planetary Science—Strongly recommended but not required.

Applicants from non-English-speaking nations are required to submit Test of English as a Foreign Language (TOEFL) scores.

Based on their applications and interests, students enter one of the major subject options of the division and are given an academic adviser who is a professorial faculty member associated with the option. The six options are environmental science and engineering, geobiology, geochemistry, geology, geophysics, and planetary science. Students may later change options, but must first obtain approval from the new option. Each student must plan to satisfy the requirements for the Ph.D. degree in one option.

Entering students in the week preceding the beginning of instruction for the first term meet with their option representatives to discuss their preparation in the basic sciences and select a series of courses that will best prepare them for research in their chosen field while meeting the requirements set forth below.

First-year graduate students are encouraged to register for at least nine units of research (Ge 297) in each term of residence. The primary objective is to communicate to the students the excitement of discovery based on original investigations and to provide a broad scope of research aims. An important byproduct can be the formulation of propositions for the Ph.D. qualifying oral examination or orientation toward Ph.D. research.



*Advising and Thesis Supervision*

The academic adviser appointed after the first quarter for each incoming student continues as mentor with broad responsibility for a student's academic welfare throughout the graduate program. During the second year, after passing the qualifying examination, each student should identify a professor as thesis adviser, who will normally provide a graduate research assistantship and the opportunity for continuing research. In consultation with the two faculty advisers, each student then forms a thesis advisory committee composed of at least four Caltech professors (chaired by the academic adviser). External scientists closely involved in the student's research may also be appointed. Members of the committee serve as advisers, counselors, and resources. Committee membership may be changed if a student's research interests change.

The thesis advisory committee meets with the student at least once each year for a progress review, and informally whenever the student needs or requests assistance or guidance. In addition, the

faculty members in each option have their own systems for annual evaluations of student progress. A few months before completion of the thesis dissertation, the thesis examining committee will be chosen, usually including the members of the thesis advisory committee.

All students are urged to consult with division faculty in the following sequence if they have any problems: thesis and academic advisers, thesis advisory committee, option representative, academic officer, and division chair. If these division personnel cannot resolve a problem, then the student should turn to Institute offices.

*Master's Degree*

Students enrolled in the Ph.D. program may be awarded a master's degree when they have satisfied the basic Institute requirement of 135 units. These courses must be numbered 100 or higher, and must be part of those used to satisfy the Ph.D. requirement in one of the options of the division. Specifically required are Ge 109 and two courses from the list Ge 101, Ge 102, Ge 103, Ge 104, or ESE/Ge 148 a.

An application for admission to candidacy for an M.S. degree must be submitted to the Graduate Office according to the academic calendar in the *Caltech Catalog* (see pages 4–5).

*Doctoral Degree: Division Requirements*

For a Ph.D. degree, the student must 1) pass the qualifying oral examination, 2) satisfy course requirements of the division and of an option, and 3) complete a thesis and successfully defend it in a final oral examination. Admission to candidacy occurs after the student has satisfied the first two requirements and has been accepted for thesis research by a division faculty member, who then becomes the student's thesis adviser.



The qualifying examination consists of oral and written defense of two research propositions, supplemented by a written description of one of them. Students are encouraged to consult with various staff members concerning their ideas on propositions, but the material submitted must represent the work of the student. There must be a different faculty member associated with each of the two propositions. The exam is normally taken early in the first term of the second year of residence and is administered by the qualifying examination committee, which has members from the six options of the division. A more detailed outline of the qualifying examination is available on the division website.

Before the end of the second year, the thesis advisory committee will be selected, as outlined above.

The division encourages students to engage in research early in their graduate careers. Students making normal progress will submit to refereed journals papers that have been approved by a faculty member of the division. Doctoral candidates must complete

a thesis and submit it in final form by May 10 of the year in which the degree is to be conferred. The final oral examination for the doctorate by the thesis examining committee will be scheduled no sooner than two weeks following submission of the thesis (approved by the thesis adviser) and, in conformity with Institute regulations, it must be scheduled at least two weeks before the degree is to be conferred.

Candidates are expected to publish the major results of their thesis work. The published papers should have a California Institute of Technology address. Published papers may be included in the thesis.

By the end of the first academic year (third term): submission by the student of (1) tentative titles of propositions for review by the qualifying examination committee and (2) a list of courses planned to satisfy the Ph.D. requirement, for review by the option.

By the end of the second academic year: (1) passage of oral exam; (2) approval by the option of courses planned to satisfy candidacy requirements; (3) submission of a tentative thesis topic and adviser, and thesis advisory committee.

By the end of the third academic year: (1) satisfactory completion of course requirements; (2) satisfactory completion of other requirements including selection of thesis topic and adviser, and thesis advisory committee; (3) admission to candidacy. A student who has not been admitted to candidacy by the end of the third year will need permission of the academic officer to register.

By the end of the fourth academic year: satisfactory progress toward completion of thesis.

After completing the fifth academic year, the student must formally petition to register for each subsequent year. Financial aid will normally not be extended beyond the sixth year.



The student's program and progress will be reviewed annually by his or her option and by the thesis advisory committee. In cases where, in the opinion of the faculty in the option, the student is clearly not showing adequate progress, they may recommend to the division chair that the student be denied permission to continue in the Ph.D. program based upon their overall assessment of the student's performance.

*Basic Division Course Requirement*

During the first year, every graduate student will take two of the five basic introductory courses Ge 101–104 and ESE/Ge 148 a, in areas in which the student has not had substantial training. Also required is one term of Ge 109. Throughout their graduate careers, students are expected to attend departmental seminars and seminar courses led by visiting scientists.

*Requirements of the Major Subject Options*

*Geobiology.* In addition to the general Institute and basic division requirements, candidates for the Ph.D. degree in geobiology must

successfully complete a minimum of 90 units at the 100 or greater level, including Ge 104; either Bi/Ch 110 or ACM/ESE 118; and two courses from each of the following three subject menus:

Geology: Ge 106 ab, 112, 114 ab, 124.
Chemistry: ESE 142, Ge/ESE 143, 149, Ge 140, ESE/Ge/Ch 171, 172.
Biology: ESE/Bi 166, 168, Ge/ESE 170, Bi 117, ESE/Ge 148 c.

Other classes may be substituted for these menu requirements with the approval of the option representative. A student with substantial prior experience in geobiology (e.g., an M.S. degree) may use prior course work to substitute up to 45 of these units with the approval of the geobiology option representative. All students must have a basic knowledge of organic chemistry at the level of Ch 41 a. This requirement may be met by previous course work or through successful completion of this class.

*Geochemistry.* In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in geochemistry are required to demonstrate an understanding of the field through a total of 90 units of course work at the 100 level or higher spread over four of the subdisciplines offered in the option: petrology/mineralogy, isotope geochemistry, cosmochemistry, water chemistry/oceans, atmospheres, and biogeochemistry. A student with substantial prior experience in some of the subdisciplines may use prior course work to substitute for up to 45 of these units with the approval of the geochemistry option representative. In the oral candidacy exam, the student will be subject to examination in all four of the chosen subdisciplines. All students must have a basic knowledge of chemistry at the level of Ch 21 and mathematics at the level of Ge 108.



*Geology.* The geology option requirements are (1) two of Ge 102, 103, 104, or ESE/Ge 148 a, which also satisfy the basic division requirement; (2) 36 units in 100-level science or engineering courses taken outside the GPS division, or in courses cross-listed with other divisions. Ch 21 abc may be included as part of these units, and other courses below the 100 level may be included at the discretion of the option representative. Students with a focus in planetary geology may use 100-level planetary science courses to fill this requirement; (3) 36 units of advanced field geology, in the form of three terms of Ge 121 abc taken from three different instructors; (4) an additional 18 units of 100- or 200-level courses within the GPS division. Courses that cannot be used to satisfy these requirements include research and reading courses, and certain courses constituting basic preparation in the field of geology, such as Ge 106, Ge 112, Ge 114 ab, and Ge 115 abc. A grade of C or better is required for all course work that satisfies these requirements. Knowledge of basic physics, mathematics, and data analysis at the level of Ge 108 and ACM/ESE 118 is required of all Ph.D. candidates in geology. Students entering the geology option with a master's degree in a science or mathematics may be exempt from

up to 45 units at the discretion of the option representative (exemptions from advanced field geology must be granted by the GPS field committee).

*Geophysics.* In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in geophysics must successfully complete the following course requirements: two of Ge 101, 103, 104, or ESE/Ge 148 a; either Ae/Ge/ME 160 ab, APh 105 ab, MS 115 ab or a subject equivalent; three of Ge 161, Ge 162, Ge 163, or Ge 164, and Ge 111 ab, and the choice between a minor in any field at Caltech or five additional 100- or 200-level science or mathematics courses. It is highly recommended that these courses be taken in the first year. Students may substitute another course for a required course if they can demonstrate to an option representative that they have already had the material in the required course.

*Planetary Science.* In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in planetary science must satisfy the following course requirements: Ge 101, Ge 102, and courses in planetary formation and dynamics (Ge/Ay 133), planetary atmospheres (Ge 150), planetary interiors (Ge 131), and planetary surfaces (Ge 151). In addition, students shall successfully complete 45 units of 100-level or higher courses in a coherent field of specialization. This requirement may be satisfied by completion of a subject minor or through a set of courses chosen in consultation with and approved by the adviser and the option representative. All candidates are expected to possess knowledge of physics and mathematics at the level of Ph 106 and ACM 95. This requirement may be met by previous course work or through successful completion of these classes.



*Subject Minor*

A student may, with the approval of the Division of Geological and Planetary Sciences, elect a minor in any one of the major subjects listed above. Such a subject minor will include at least 45 units in courses at the 100 level or higher. Normally, a member of the division faculty will participate in the student's oral thesis defense.

## History

The program for a subject minor in history must be approved by the executive officer for the humanities before the admission to candidacy. In addition to meeting general Institute requirements, the student must complete satisfactorily, with a grade of C or better, 45 units in advanced courses in history.

## History and Philosophy of Science

Graduate students in science, mathematics, or engineering may take a minor in history and philosophy of science (HPS). The graduate minor is devoted to the study of the historical evolution

and philosophical underpinnings of the physical and biological sciences. Historical work in the minor includes the origins of experimental practice, the social and institutional contexts of science, the origins and applications of quantitative methods, specific developments since antiquity in physics, biology, and chemistry, as well as biographical and comparative studies. Philosophical research deals with issues in causation, explanation, scientific inference, the foundations of probability and decision theory, philosophy of mind and psychology, philosophy of neuroscience, and scientific fraud and misconduct.

The minor thus fosters the acquisition of broad knowledge about the scientific enterprise and related foundational problems, as well as more detailed analysis of the progress of and philosophical problems in particular branches of science. It is a valuable supplement to a technical degree since it helps equip students to understand the nature of scientific progress and to grapple with the conceptual basis of science and its wider ramifications. Students who successfully complete the HPS minor will be recognized with official credit for the achievement on their transcripts.

*Requirements*
Graduate students who take an HPS minor are expected to complete Hum/H/HPS 10, HPS 102 ab, HPS/Pl 120, at least three units of HPS 103, and 18 units of additional work in HPS, to be completed by taking courses in HPS/H or HPS/Pl numbered 99 or higher. Students need not complete the requirements for the minor within the first two years of graduate study.

## Materials Science



*Aims and Scope of the Graduate Program*
The graduate program is designed to give students an understanding of general phenomena in synthesis–structure–property relationships in all materials, plus a detailed understanding of phenomena for at least one particular class of materials. After completing the Ph.D. program, students will be qualified for careers in teaching and research at colleges and universities, in research for government and industry, in the operation and control of manufacturing processes, and in the management and development positions in the materials industry. Students may enter the graduate program in materials science with undergraduate preparation in physics, chemistry, engineering, or materials science. Students interested in terminating their graduate study at the master's level are not normally admitted. Students in the Ph.D. program are required to complete a set of core courses, pass an oral candidacy examination, complete a thesis describing original research in materials science or a related field, and publicly defend their thesis work.

*Master's Degree*

Each student is assigned to a member of the faculty who will serve as the student's adviser. The adviser and option representative for materials science will approve his or her course of study.

Study for the degree of Master of Science in materials science will ordinarily require three terms of courses. The courses shall be chosen from the list of core courses below, although 27 units of research (MS 200 or equivalent) may be substituted for 27 units of lecture or laboratory courses. Completion of 138 units of these courses within two years with no grade less than a C constitutes the academic requirements for the M.S. degree.

*Core Courses*

1. MS 131, MS 132, MS 133.
2. APh 105 a or ChE/Ch 165, APh 105 b or ChE/Ch 164, MS 105.
3. Two quarters of courses focused on specific materials, such as APh 114 ab; Ch/ChE 147, ChE/Ch 148; Ge 114, Ge 214.
4. Two quarters of courses focused on internal interactions in materials, such as Ph 125 ab, Ch 125 ab; Ae/AM/CE 102 abc or Ae/Ge/ME 160 ab; Ch 120 a; Ch 121 ab.
5. 18 units of courses comprising either the third terms of the sequences taken in 3 and 4 above, or other courses appropriate for the student's research interests, such as MS 125, 142, MS/EST 143, MS/ME 161, 162.
6. Mathematics at the level expected of research in the student's field. This may be satisfied by the courses ACM 100, or AM 125 abc, or ACM 101 abc, or Ph 129 abc, or may be waived at the discretion of the student's adviser and option representative.
7. MS 110 abc (3 units) or APh 110 (2 units) or E 150 abc (3 units), seminar.



*Degree of Doctor of Philosophy*

*Residency.* Work toward the degree of Doctor of Philosophy in materials science requires a minimum of three years following the completion of the bachelor's degree or equivalent.

*Language Requirement.* There is no language requirement for the Ph.D. degree.

*Minor.* No minor is required for the Ph.D. degree. Students are, however, encouraged to take advanced courses appropriate to their particular interests.

*Advising and Thesis Supervision.* In the first year, each student must choose a research adviser who will have primary responsibility for supervising the student's course program and research. The important adviser–advisee relationship requires effort from both parties, and some general expectations are outlined earlier in this section of the catalog. In addition, each student who has passed the candidacy examination shall select a faculty mentor, who will review the student's progress at least annually.

*Admission to or Continuation in Ph.D. Status.* To be advanced to candidacy for the doctor's degree, the student must satisfy three requirements:

a. *Courses.* To continue in the graduate program, the student must maintain a B– average for each term. Advancement to candidacy requires the successful completion of the program listed under "Core Courses" above. Alternatively, if the student has taken equivalent courses elsewhere, he or she must prove competency in these areas through an oral examination in each subject.
b. *Oral Candidacy Examination.* The student will prepare a brief presentation on a topic in his or her proposed area of research. The core of the examination is based on the student's course work and how it is related to the topic of the presentation. This examination should be taken no later than the end of the student's second year of residence.
c. *Research Competence.* The student must have a doctoral research adviser, and must have completed at least 18 units of MS 200.

*Thesis and Final Examination.* The candidate is required to take a final oral examination covering the doctoral thesis and its significance in and relation to his or her major field. It will consist of a public thesis seminar and an associated oral examination on the thesis and related fields. This examination will be held at least two weeks after the doctoral thesis has been presented in its final form, and prior to its approval. This examination must be taken at least four weeks before the commencement at which the degree is to be granted.



*Subject Minor*
A student majoring in another option at the Institute may elect a subject minor in materials science. He or she must obtain approval from the materials science faculty of a course of study containing at least 45 units of advanced courses. Normally a member of the materials science faculty will participate in the candidacy examination in the student's major department.

## Mathematics

*Aims and Scope of the Graduate Program*
The principal aim of the graduate program is to develop the student's ability to do original research in mathematics. Independent and critical thinking is fostered by direct contact with faculty members. (An indication of the current research interests of the faculty begins on pages 117–118.) Faculty advisers help students plan their programs of study leading to a Ph.D. in mathematics. Entering students are advised by the director of the Ph.D. program, who assists them in selecting appropriate courses, depending upon their previous studies.

*Course Program*

The graduate courses are listed in section five. The three core courses—Ma 110 in analysis, Ma 120 in algebra, and Ma 151 in geometry and topology—are required of all graduate students unless excused by the director of the Ph.D. program. Students are expected to complete these core courses in preparation for the qualifying examinations (see below), usually in the first year. (Entering students are allowed to take a qualifying examination in September or October in order to demonstrate knowledge of one or more of the core areas. By passing the examination, they are excused from taking the corresponding course.) In addition, students are required to complete nine quarters of other advanced mathematics courses, at least two of which are in discrete mathematics: combinatorics, complexity, and computability, or logic and set theory. Under special circumstances (e.g., finishing the degree in three years), exceptions to these requirements may be granted by the director of the Ph.D. program.

Beginning no later than the second year, students will be expected to begin independent research work and will be strongly encouraged to participate in seminars.

*Master's Degree*

Entering graduate students are admitted directly to the Ph.D. program, since the Institute does not offer a regular program in mathematics leading to the master's degree. A master's degree may be awarded in exceptional circumstances either as a terminal degree or preliminary to the Ph.D. Sufficiently advanced undergraduates may be admitted to graduate standing to pursue a master's degree simultaneously with the bachelor's program.



The recipient of a master's degree will be expected to have acquired, in the course of studies as an undergraduate or graduate student, a comprehensive knowledge of the main fields of mathematics comparable to 180 units of work in mathematics with course numbers greater than 90.

The general Institute requirements specify that the recipient of a master's degree must have taken at least 135 units of graduate work as a graduate student at the Institute, including at least 81 units of advanced graduate work in mathematics. This advanced work is interpreted as work with a course number greater than 109 and may include a master's thesis.

*Degree of Doctor of Philosophy*

*Qualifying Examinations.* Qualifying examinations in the three core areas—analysis, algebra, and geometry/topology—are offered in October and June. These examinations emphasize mastery of the basic concepts and theorems and the ability to apply them to specific cases. Students are required to take and pass two of the three examinations, and for the one not taken, to complete the

corresponding core course with a grade of B of better. Normally, the examination requirements are completed at the end of the first year or the beginning of the second.

*Summer Study.* Although there are no courses given in the summer, graduate students are expected to carry out studies and research in their chosen area of mathematics. In the summer after the first year, they will work under the guidance of a faculty member to investigate a possible area for their thesis research.

*Thesis Adviser.* It is expected that by the fall quarter of the second year, students will find a member of the faculty who agrees to serve as their thesis adviser. The progress of all continuing students is assessed by the faculty each fall, and students will consult with their advisers about their progress and planning of their studies and research.

Students receive help and advice not only from their thesis adviser and other faculty mentors, but also whenever needed from the director of the Ph.D. program, the executive officer, and the faculty ombudsperson in mathematics. (See also the section with guidelines for graduate student advising on page 243.)

*Admission to Candidacy.* Before the end of their third year, students are expected to finish the process of applying for admission to candidacy for the Ph.D. degree. This formal step requires completion of the requirements for qualifying examinations and core courses, as well as a satisfactory oral presentation to a committee of faculty members. The presentation will describe both the general area of the student's proposed thesis research and the specific problem or problems to be addressed. A written summary of the presentation, typically 3–10 pages, must be given to the committee members at least one week before the presentation. The student and his or her adviser will arrange the formation of this committee, which will have three members, including the adviser.



*Thesis and Final Examination.* On or before the first Monday in May of the year in which the degree is to be conferred, candidates for the degree of Doctor of Philosophy must deliver copies of their theses to their advisers, to the Graduate Office, and to the members of the committee that will conduct the final oral examination on the thesis. The examination must be held at least three weeks before the date on which the degree will be conferred and at least two weeks after the delivery of the copies of the thesis.

*Subject Minor*

Students majoring in other fields may take a subject minor in mathematics. Minor programs must include 54 units of advanced work approved by a representative of the mathematics department, who will ensure that the work represents a concentrated study in one or more of the main fields of mathematics. A special oral examination in the subject minor will be given soon after completion of the minor program.

*Travel Grants*
Special funding is available to graduate students to attend conferences and workshops in the United States or abroad (see Bohnenblust Travel Grants on page 260).

## Mechanical Engineering

*Aims and Scope of the Graduate Program*
The aim of the graduate program in mechanical engineering at Caltech is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program combines individual depth of experience and competence in a particular chosen major specialty, and a strong background in the basic and engineering sciences, with laboratory and design experience. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Original research in mechanical engineering is an essential component of the graduate program. Independent and critical thinking is encouraged by participation in seminars and by discussions with faculty members. Research groups in mechanical engineering are small, creating an environment where students work closely and collaboratively with the faculty.

The degrees of Master of Science, Mechanical Engineer, and Doctor of Philosophy are offered.

Research areas in mechanical engineering at Caltech include mechanics (including active materials, fracture mechanics, and mechanics of materials), mechanical systems (including control and analysis of dynamic systems, engineering design of electromechanical systems, design theory and methodology, kinematics, optimization, robotics, and structural design), and fluid and thermal systems (including acoustics, cavitation, chemical vapor deposition, combustion, fluid flow, heat and mass transport, multiphase and multicomponent flows, propulsion, and turbulence). Research in these areas is applied to a wide variety of problems including control of aircraft engines, design of vehicle structures, granular flows, hyper-redundant robots, jet noise reduction, locomotion and grasping, medical applications of robotics, navigation algorithms, structured design of micro-electro-mechanical systems (MEMS), thin film deposition, transportation systems, propulsion systems, explosion dynamics including deflagrations, detonations, and shock waves, and rapid assessment of early designs.



*Admission*
As preparation for advanced study and research, entering graduate students must have a thorough background in undergraduate mathematics, physics, and engineering. An outstanding four-year undergraduate program in mathematics and sciences may be substituted for an undergraduate engineering course, with the

approval of the faculty. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty. In some cases the student may be required to make up undergraduate deficiencies in engineering science courses. However, in every case the student will be urged to take some courses that will broaden his or her understanding of the overall field, as well as courses in the specialty. Most graduate students are also required to take further work in applied mathematics.

*Master's Degree*

The degree of Master of Science in mechanical engineering provides the student with advanced training beyond the undergraduate fundamentals, and may include an introduction to research. A minimum of 138 units of courses numbered 100 or above, that meet the distribution requirements listed below, must be passed with a grade of at least C for completion of the master's degree in mechanical engineering. All units must be taken for grades, except for courses offered only on a pass/fail basis. Each student's program must be approved by the option representative in mechanical engineering.

*Required Program*

- Graduate mechanical engineering core—54 units. These units should provide a solid base for the student's engineering interest. The courses may be selected from the following list: Ae/APh/CE/ME 101 abc, Ae/Ge/ME 160 ab, ME 118, ME 119 ab, Ae/ME 120 ab, Ae/AM/CE 102 abc, AM/CE 151 ab or CDS 140 ab, and CDS 110 ab.
- Mathematics, engineering, and research electives—54 units. Students who have not taken the equivalent of ACM 100 abc are required to take ACM 100 abc for 36 units. Mechanical engineering students are urged to consider taking 27 units of courses in automation and robotics (ME 115 ab, ME 131, ME/CS 132); multi-phase flows (ME 202 abc); propulsion (Ae 121 abc); experimental methods (Ae/APh 104 abc); or any additional courses listed in the graduate mechanical engineering courses. Other courses may also be taken in Ae, AM, ACM, ME, JP, MS, EE, ESE, APh, CDS, CS, ChE, and CNS. Students who are considering study beyond the master's degree are encouraged to take research units, ME 300, up to a maximum of 27.
- Free electives—27 units. These units may be selected from any course with a number of 100 or greater, except that research units may not be included.
- Engineering seminar, ME 150 abc—3 units.

Students admitted for study toward a master's degree but interested in pursuing subsequent study toward a Ph.D. degree should also read the section below relating to this degree.

*Degree of Mechanical Engineer*

Greater specialization is provided by work for the engineer's degree than by work for the master's. The degree of Mechanical Engineer is considered to be a terminal degree for the student who desires more highly specialized advanced training with less emphasis on research than is appropriate to the degree of Doctor of Philosophy. However, research leading to a thesis is required for both degrees. The student should refer to Institute requirements for the engineer's degree.

Not less than 55 units of work shall be for research and thesis; the exact number shall be determined by a supervising committee, appointed by the dean of graduate studies. Courses should be closely related to mechanical engineering. The specific courses (to be taken and passed with a grade of C or better by the candidate) will be finally determined by the supervising committee. The courses must include an advanced course in mathematics or applied mathematics, such as AM 125 abc or ACM 101 abc, that is acceptable to the faculty in mechanical engineering. A suitable course program may usually be organized from the more advanced courses listed under Ae, AM, ACM, CDS, JP, ME, and MS.

*Degree of Doctor of Philosophy*

The Ph.D. degree in mechanical engineering is focused on research, and prepares students to develop new understanding and advanced technology to address contemporary problems. Study and research programs for the Ph.D. degree are individually planned to fit the interests and background of the student. A comprehensive research project resulting in an original contribution to the field documented by a dissertation is required. Institute requirements for the Ph.D. degree are described in the section on degree requirements. Approximately two years of course work are required, and two or more additional years are usually needed for preparation of the dissertation.



*Advising and Thesis Supervision.* An interim adviser is appointed for each student upon admission to a graduate degree in mechanical engineering. The interim adviser will serve as the primary mentor until the student finds a research adviser.

It is the responsibility of the student to find an academic and research adviser within three terms of graduate residence at Caltech. In consultation with the adviser, the student must form a Ph.D. dissertation supervision committee within one year of graduate residence at Caltech. This committee shall consist of at least three members of the Caltech professorial faculty, with at least two members from the faculty in mechanical engineering. The adviser shall serve as chair of this committee. This committee shall meet as requested by the student. Further, this committee shall meet annually to review progress and to approve the registration of the student beyond the fifth year of graduate residence at Caltech.

The adviser and the thesis supervision committee provide the majority of mentoring to the student. In addition, the option representative and other members of the faculty are always available to provide advice and mentoring on any aspect of research, progress toward the Ph.D., future careers, and other aspects of life in graduate school and as a professional scientist.

*Admission to Candidacy.* To be recommended for candidacy for the Ph.D. degree in mechanical engineering, the student must, in addition to meeting the general Institute requirements, do the following:

- Obtain the agreement of a professorial faculty member to serve as his or her academic and research adviser and form a three-member dissertation supervision committee with the adviser as the chair.
- Successfully complete at least 54 units of research and demonstrate satisfactory research progress.
- Pass with a grade of at least C a minimum of 18 units of course work in any three core mechanical engineering subjects spanning at least two broad areas listed below. Examples of suitable courses are given in parentheses.

*Area 1*
Fluid Mechanics (Ae/APh/CE/ME 101 abc)
Mechanics of Structures and Solids (Ae/AM/CE/ME 102 abc)
Continuum Mechanics of Solids and Fluids (Ae/Ge/ME 160 ab)

*Area 2*
Thermodynamics and Statistical Mechanics (ME 118, APh 105, Ch/ChE 164, Ch 166)
Heat and Mass Transfer (ME 119 ab)
Combustion (ME 120 ab)
Energy (EST/EE/ME 109 ab)

*Area 3*
Dynamical Systems (AM/CE 151 ab or CDS 140 ab)
Mechanical Systems and Design (ME 115 ab)
Controls (CDS 110 ab, CDS 212)

The student may petition the mechanical engineering faculty to accept alternate subjects or areas. These changes should retain core mechanical engineering knowledge and represent sufficient breadth. The petition must be submitted to the option representative and approved before the student registers for the course.

These 54 units may also be used in the student's program for the master's degree. Students must do the following:

- Pass with a grade of at least C an additional 54 units (with a course number above 100) that pertain to the student's specialty and are approved by the dissertation supervision committee in engineering or science.

- Pass with a grade of at least C 27 units of advanced courses in mathematics or applied mathematics chosen in consultation with their adviser from the following list: ACM 101 or higher, AM 125, CDS 201, CDS 202, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above and cannot be counted toward a minor.
- Pass both subject and research components of the oral candidacy examination. If the student has chosen a subject minor, an examination on the subject of that program may be included at the request of the discipline offering the subject minor. The oral candidacy examination must be taken before the end of the second year of graduate academic residence at the Institute.

The requirement of a minimum grade of C will be waived for an advanced course which (i) lists one of the courses in Areas 1, 2, and 3 as a prerequisite, and (ii) is offered only pass/fail.

The faculty will evaluate the student's research progress, class performance, adviser's input, and oral candidacy exam results to determine whether a student will be admitted to candidacy for the Ph.D. degree.

*Registration Beyond Fifth Year of Graduate Residence.* The annual approval of the Ph.D. dissertation supervision committee is necessary for registration beyond the fifth year of graduate residence at Caltech.

*Thesis and Final Examination.* The thesis examination will be given after the thesis has been formally completed. This examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in the specialized field of research. The format of the examination will be a public seminar presented by the candidate, with an open question period, followed by a private examination by the examining committee. The examining committee shall consist of at least four Caltech professorial faculty members, at least three of whom shall be from the Division of Engineering and Applied Science, and at least two of whom shall be mechanical engineering faculty members. One member of the committee shall be from outside the student's area of Ph.D. research. The student's adviser shall act as chair of the committee.



*Subject Minor*

A student majoring in another branch of engineering or another division of the Institute may, with the approval of the faculty in mechanical engineering and the faculty in his or her major field, elect mechanical engineering as a subject minor. The program of courses must differ markedly from the major subject of study or research, and must consist of at least 54 units of advanced work.

## Physics

*Aims and Scope of the Graduate Program*
The physics option offers a program leading to the degree of Doctor of Philosophy. This program prepares students for careers in scientific research or research combined with teaching, and so its most important part is independent research. Courses are offered that give a broad treatment of both fundamental physics and specialized physics research topics. These are intended both to help a beginning graduate student prepare for research and to broaden an advanced student's knowledge of physics. Caltech research opportunities include elementary particle physics, nuclear physics, cosmic-ray, gamma-ray, and X-ray astronomy, submillimeter astronomy, condensed-matter physics, atomic/molecular/optical physics, quantum optics, applied physics, gravitational physics, cosmology, astrophysics, mathematical physics, biophysics, and theoretical physics.

A Master of Science degree may be awarded upon completion of a program of courses. Students are not normally admitted to work toward the M.S. in physics unless they are also working toward a Ph.D.

*Admission*
Application forms for admission to graduate standing and for financial assistance can be obtained from the Office of the Dean of Graduate Studies, California Institute of Technology, Pasadena, CA 91125, or can be downloaded from http://www.gradoffice.caltech.edu. Completed applications should reach the Graduate Office by January 15. Applicants are strongly advised to take the Graduate Record Examination (GRE) and the Advanced Physics Test. Information can be obtained from the Educational Testing Service, 20 Nassau Street, Princeton, NJ 08540 (http://www.ets.org).



*Placement Examinations*
Students admitted to work for an advanced degree in physics are required to take placement examinations, typically given the Monday of general orientation week before the student's first term of graduate study. These informal exams are used as a guide in selecting the proper course of study. The exams cover material in classical mechanics, electromagnetism, quantum mechanics, statistical mechanics, and mathematical physics. In general, they will be designed to test whether the student possesses an understanding of general principles and the ability to apply these to concrete problems, rather than detailed informational knowledge. The results of the placement exams are not formally recorded as a part of the student's record. In cases in which there is a clear basis for ascertaining the status of the entering graduate student, the placement exams may be waived.

*Master's Degree*

A Master of Science degree in physics will be awarded, upon request, to physics Ph.D. students who have completed the oral and written candidacy examinations. Alternatively, a master's degree will be awarded to any Caltech graduate student in good standing upon satisfactory completion of a program approved by the option representative that fulfills the following requirements:

| | |
|---|---|
| Ph 125 abc<br>(If this course, or its equivalent, was taken as part of an undergraduate program, it may be replaced by 27 units of any quantum-mechanics–based course.) | 27 units |
| Physics electives<br>These must be selected from Ph 103, Ph 105, Ph 118, Ph 127, Ph 129, Ph 135, Ph 136, or physics courses numbered 200 or above. | 81 units |
| Other electives<br>These must be graduate courses from physics or any other option, including the humanities. | 27 units |

Substitutions of other graduate courses in place of the above requirements must be approved by the option representative.

In exceptional cases, undergraduate students may receive concurrent B.S./M.S. degrees if the above requirements are met in addition to the relevant B.S. requirements, upon approval from the Physics Graduate Committee, the graduate admissions committee, and the physics executive officer. Such students must produce a detailed petition demonstrating accomplishments that would warrant normal admission to the physics graduate program.



*Degree of Doctor of Philosophy*

In addition to the general Institute requirements for a Ph.D., the particular requirements for a doctorate in physics include admission to candidacy as described below, writing a thesis that describes the results of independent research, and passing a final oral examination based on this thesis and research. Physics graduate students may exercise the pass/fail option on any and all courses taken.

*Admission to Candidacy.* To be admitted as a candidate for a Ph.D., a student must pass two terms of Physics Seminar (Ph 242), pass written candidacy examinations covering basic physics, satisfy the Advanced Physics requirements described below, and pass an oral candidacy examination. These requirements are designed to ensure that students have an adequate preparation in the basic tools of physics, as well as a broad general knowledge of advanced physics.

*Basic Physics Requirement.* To be admitted to candidacy, physics students must demonstrate proficiency in all areas of basic physics, including classical mechanics (including continuum mechanics),

electricity and magnetism, quantum mechanics, statistical physics, optics, basic mathematical methods of physics, and the physical origin of everyday phenomena. A solid understanding of these fundamental areas of physics is considered essential, so proficiency will be tested by written candidacy examinations.

No specific course work is required for the basic physics requirement, but some students may benefit from taking several of the basic graduate courses, such as Ph 106, Ph 125, and Ph 127. A syllabus describing the exam contents will be available, and students are encouraged to study independently for the exams, rather than taking a heavy load of basic physics courses.

The written exams are offered at frequent intervals, typically once per term, and the separate sections may be taken at different times. This flexible scheduling of the written exams allows students to prepare for the exams while simultaneously learning about research areas, either through advanced courses, reading courses, or participation in a research group.

*Advanced Physics Requirement.* In addition to demonstrating a proficiency in basic physics, students must also establish a broad understanding of modern physics through study in six of the following eight areas of advanced physics:

1. elementary particle physics
2. nuclear physics
3. atomic/molecular/optical physics
4. condensed-matter physics
5. gravitational physics
6. astrophysics
7. mathematical physics
8. interdisciplinary physics (e.g., biophysics, applied physics, chemical physics)

The advanced physics requirement can be fulfilled by passing exams in the separate areas, or by passing courses. Each area is meant to be covered by the equivalent of a one-term course. There will be a list of course substitutions for each of the areas, which will include courses outside of physics. Other courses may be substituted with permission from the Physics Graduate Committee.

*Oral Candidacy Exam.* This exam is primarily a test of the candidate's suitability for research in his or her chosen field. The chair of the examination committee will be the professor the student plans to do research with, and normally the student will have already begun research (Ph 172 or Ph 173) on a definite topic with that professor. The examination will cover the student's research work and its relation to the general field of specialization. Before being allowed to take this exam, a student must have satisfied all the other requirements for admission to candidacy.

*Research Requirements.* There are no specific research requirements, but in general a substantial effort is required to master the techniques in a given field and carry out a significant piece of original research. Students are strongly advised to start doing part-

time research as soon as possible, and to carry it on in parallel with formal course work, taking reading and research units (Ph 171–173) prior to being admitted to candidacy. Typically, students continue graduate study and research for about two years after admission to candidacy.

*Scheduling.* Although students are encouraged to begin doing research soon after arriving at Caltech, they should also try to complete the requirements for candidacy as quickly as possible before focusing completely on a particular research area. Thus Ph 242 should be taken by all students in their first year of graduate study. The written candidacy exams should be attempted by the end of a student's first year of study, and be passed by the end of the second year. The Advanced Physics requirements should also be completed by the end of the second year, but may be extended into the third year depending on the availability of specific courses. If these deadlines are not met, a student must petition the Physics Graduate Committee before registration for subsequent terms will be allowed.

*Advising and Thesis Supervision.* After taking the placement exams described above, physics graduate students meet with the chair of the admissions committee to decide on a first-year course schedule. At this time it is appropriate for students, especially those admitted with GRAs, to consult with the admissions chair, the option representative, the executive officer, and/or individual faculty members to select a tentative research group, if this hasn't already occurred over the summer. At any time, a student may consult with the option representative concerning such matters as advising and switching research groups. When the student is ready to form his or her candidacy committee, this is done in consultation with the executive officer. This committee, besides examining the student's knowledge of his or her chosen field, will consider the appropriateness and scope of the proposed thesis research. Supervision of the thesis research is the responsibility of the thesis adviser, and the student should maintain close contact with his or her adviser. In some circumstances, such as interdisciplinary work with an adviser from another department, a special committee may be formed to follow the progress of the research as well.



*The Minor.* A minor is not required, but a student may elect to pursue a minor in another option.

*Language Requirements.* There are no language requirements for a Ph.D. in physics.

*Thesis and Final Examination.* A final oral examination will be given not less than two weeks after the thesis has been presented in final form. This examination will cover the thesis topic and its relation to the general body of knowledge of physics. The candidate is responsible for completing the thesis early enough to allow the fulfillment of all division and Institute requirements, with due regard for possible scheduling conflicts.

*Subject Minor*
Students desiring a subject minor in physics should discuss their proposed program with the chair of the Physics Graduate Committee. Forty-five units are required for approval of a subject minor in physics. Physics courses with numbers over 100 will be allowed for the subject minor. At least 18 of the 45 units must be chosen from the physics electives list (see list under *Master's Degree* in this section), excluding Ph 129 and any specific courses in physics required for the student's major program. An oral exam may be required by the Physics Graduate Committee. This exam will include both academic topics and topics on current physics research areas. The oral exam may be waived if at least one term of Ph 242 has been taken successfully, or if all 45 units are in letter-graded (*not* pass/fail) courses.

## Social Science

*Aims and Scope of the Graduate Program*
The Caltech Ph.D. program in social science is designed to produce scholars who are well grounded in the theoretical perspectives, the quantitative techniques, and the experimental methods of economics and political science. Most graduates of the program work in departments of economics, political science, or public policy, or in business schools at major universities. Others have taken positions as economic analysts, program evaluators, and planners in both the public and private sectors. In addition, a special program enables students to obtain joint degrees in social science from Caltech and in law from other nearby universities. Graduates of this joint program teach in law schools, practice law, and hold other positions in academia and government.



*Master's Degree*
Entering graduate students are admitted to the Ph.D. program, and will earn the M.S. degree after successful completion of 135 units of course work. The program does not admit students who plan to obtain an M.S. degree only, but a student who does not go on to achieve a Ph.D. may leave with a terminal master's degree.

*Admission*
Admission to the Caltech Ph.D. program is highly competitive, and those who are admitted have excellent GRE scores, impressive academic records as undergraduates, and highly supportive letters of recommendation. Entering students are expected to have a strong background in mathematics, and to have completed courses in calculus at the levels of Ma 2, linear algebra, and mathematical statistics. A course in real analysis is also highly desirable. Students are expected to take additional mathematics courses when relevant to their research.

*Course Program*

The program is designed to enable students to earn their Ph.D. in five years, although it is sometimes possible to finish in four years. During their initial two years in the program, students are expected to acquire competence in the core areas of economics, analytical politics, and econometrics. In the third year, students are expected to begin their dissertation research while they continue to acquire skills. The fourth and fifth years are devoted to research and writing, culminating in the Ph.D. dissertation and the granting of a Ph.D.

The first-year curriculum consists of the following four three-quarter course sequences: decision theory, game theory, and social choice (SS 201 abc); political institutions and political behavior (SS 202 abc); foundations of economics (SS 205 abc), and econometrics (SS 222 abc). All courses are nine units each, so students must register for at least 36 units each quarter. In order to make satisfactory progress, students must complete each class with a grade of B or better. The director of graduate studies (DGS) reviews each student's progress at the end of every quarter.

Second-year courses provide additional training in various subfields of social science and are designed to teach students how to conduct independent research. Many courses are designated as "workshop" courses, which are coordinated two- or three-quarter sequences in particular subfields. The sequential workshop courses are designed to provide the skills and knowledge that students need to conduct independent research and to effectively present their findings. In these courses, instructors may require a paper or project to be completed by the end of each quarter, but they may instead have students submit a more substantial paper at the end of the course sequence. Students are expected to take at least two workshop course sequences. These should be chosen in consultation with faculty members working in the area in which the student wishes to do thesis research. Workshop courses that are offered every year include Foundations of Political Economy (SS 210 abc), Advanced Economic Theory (SS 211 abc), Applications of Microeconomic Theory (SS 212 abc), Identification Problems in the Social Sciences (SS 227 abc), American Politics (SS 231 abc), and Experimental Methods of Political Economy (SS 260 abc). Courses that are offered frequently, but not necessarily every year, include Financial Economics (SS 213 abc), Advanced Topics in Econometric Theory (SS 223 abc), Theoretical and Quantitative Dimensions of Historical Development (SS 229 abc), and Historical and Comparative Perspectives in Political Analysis (SS 232 abc). Students who choose to pursue economic theory may fulfill workshop course requirements by taking a sequence of courses in mathematics, such as Classical Analysis (Ma 108), Analysis (Ma 110), Probability Theory (Ma 144), or Convex Analysis and Economics (Ec 181). As in the first year, all classes offered for grades must be completed with a grade of B or better.

SS 300 must be completed with a grade of pass. Students may take independent reading and study courses, but during the second year such courses do not count toward the 36-units-per-quarter requirement.

During the spring quarter of the second year, students should enroll in SS 300, a seminar devoted to work on their second-year paper, and the Graduate Social Science Writing Seminar (SS 281), which focuses on scholarly writing and presentation. SS 300 is taken on a pass/fail basis. By the end of their second year, each student is required to submit a research paper to the DGS. This paper must be approved by two members of the Caltech social science faculty.

During the first and second quarters of their third year, students take 15 units of Research in Social Science (SS 300), supervised by their primary adviser, and at least two other nine-unit courses. One of these courses is Modern Topics in Social Science (SS 280). This course exposes students to influential works in areas of social science that are not typically covered in the first- and second-year courses. In the third quarter, students must enroll in at least one nine-unit course along with 24 units of SS 300. Beginning in their third year and in all subsequent years, all students should also enroll in the three-unit graduate student seminar (SS 282) every quarter. Every student must make a presentation in this class at least once a year. SS 300, 280, and 282 are all taken on a pass/fail basis.

The fourth year is a yearlong thesis workshop, which means students need to register for 33 units of SS 300 and three units of the graduate student seminar SS 282, all on a pass/fail basis.

During their fifth and final year in the program, students focus on obtaining a job and on completing and defending their dissertation. Early in the first term, students need to complete a job-market paper, practice presenting that paper, and assemble and mail job applications.



*Progress Review Leading to Candidacy*

At the end of the third quarter of the first year, students are required to take a written preliminary examination which has four components, each corresponding to one of the four course sequences of the first-year curriculum. The results given are honors, pass, and fail. Students must achieve at least a pass in all four parts of the exam. Failure to do so may lead to termination from the program, but the faculty may also decide to give students who fail the opportunity to retake any or all parts of the exam before the beginning of the second year.

Students must complete a research paper, which can be co-authored, by the end of the spring term of the second year. The DGS will appoint two faculty members, normally their primary adviser and second committee member, to monitor and evaluate progress on the second-year paper. If the two faculty reviewers

find that a student's second-year paper is satisfactory, the student advances to the third year. If they do not, the social science faculty as a whole will decide whether or not the paper is satisfactory. If they decide it is not, they may also vote to terminate the student from the program.

Third-year students must write a research paper and present it to the faculty by the end of the third quarter. The paper cannot be coauthored, but should be worked on in consultation with and under the direction of the student's adviser. The paper and the presentation must demonstrate to the faculty that the student is capable of undertaking original research and presenting it to a scholarly audience. Ideally the third-year paper leads directly into dissertation research, but it is not a requirement that this be the case.

After the completion of the third-year paper presentation, the social science faculty evaluates the student's overall performance and research potential. This review is based primarily upon the third-year paper, but the faculty also verifies that the student has satisfactorily completed all previous requirements. If this evaluation is favorable, the student is admitted to candidacy for the Ph.D. At this point students need to file candidacy papers with the dean of graduate studies. If the evaluation is unfavorable, the student may be terminated from the program.

*Organization of Thesis Committee*

By February 1 of their second year, students should have decided upon the general area of social science in which they intend to pursue research and should therefore select a primary adviser whose work is related to their research interests. The adviser must be a member of the social science faculty at Caltech. The primary adviser will serve as chair of their dissertation committee. It is possible to change advisers if a student's research interests change. A second committee member, who must also be a member of the social science faculty, should be chosen by June 1 of the second year.



By the end of the third year, all students, in consultation with their advisers, should select a third committee member. This choice should be based on the content of ongoing dissertation research. It is not necessary that the third member be responsible for the full breadth of research covered by the dissertation, and in many cases the third member is selected to provide specialized help, e.g., in econometrics. Committee members may be chosen from outside the social science faculty, but such choices must be approved by the DGS. Students who are close to completing their dissertation must notify the division chairman, who will select a fourth member of the committee. The fourth member may be a member of the social science faculty, but may also come from outside the division or from another university. If the fourth member of the committee is from another university, the division will cover the cost of travel to and from Caltech for the oral defense.

*Degree of Doctor of Philosophy*

By November 1 of the fourth year, all students are required to provide the DGS with a dissertation prospectus that reviews the relevant literature, outlines the student's proposed dissertation work, and presents a tentative schedule detailing when components of the dissertation are expected to be completed. This prospectus must be approved by the adviser and the second and third committee members in the fall of the fourth year and must be filed with the DGS.

By April 1 of the fourth year, all students are required to convene a thesis proposal seminar with their adviser and other committee members. In this seminar, they are to report on the current status of their dissertation research and outline a plan and timeline for completing it. Students and their committee should thus reach a clear, mutual understanding as to what additional work needs to be done to complete and to successfully defend their dissertation. While the committee chair/adviser is primarily responsible for monitoring progress on the dissertation, students also need to consult regularly with the other members of their committee and keep them informed as to the progress they are making and any problems they are encountering. It is also expected that in the fall of their fifth year, students will present an option-wide seminar in order to prepare for the job market.

After the dissertation has been completed, students, in consultation with their adviser, must schedule the oral defense. Students must provide a written copy of their dissertation to the DGS at least two weeks prior to the oral defense date. The dissertation is expected to represent publishable, original research with a coherent theme. Successful completion implies that the faculty has certified that the student is a trained, professionally knowledgeable, and potentially productive scholar in his or her chosen area of work.