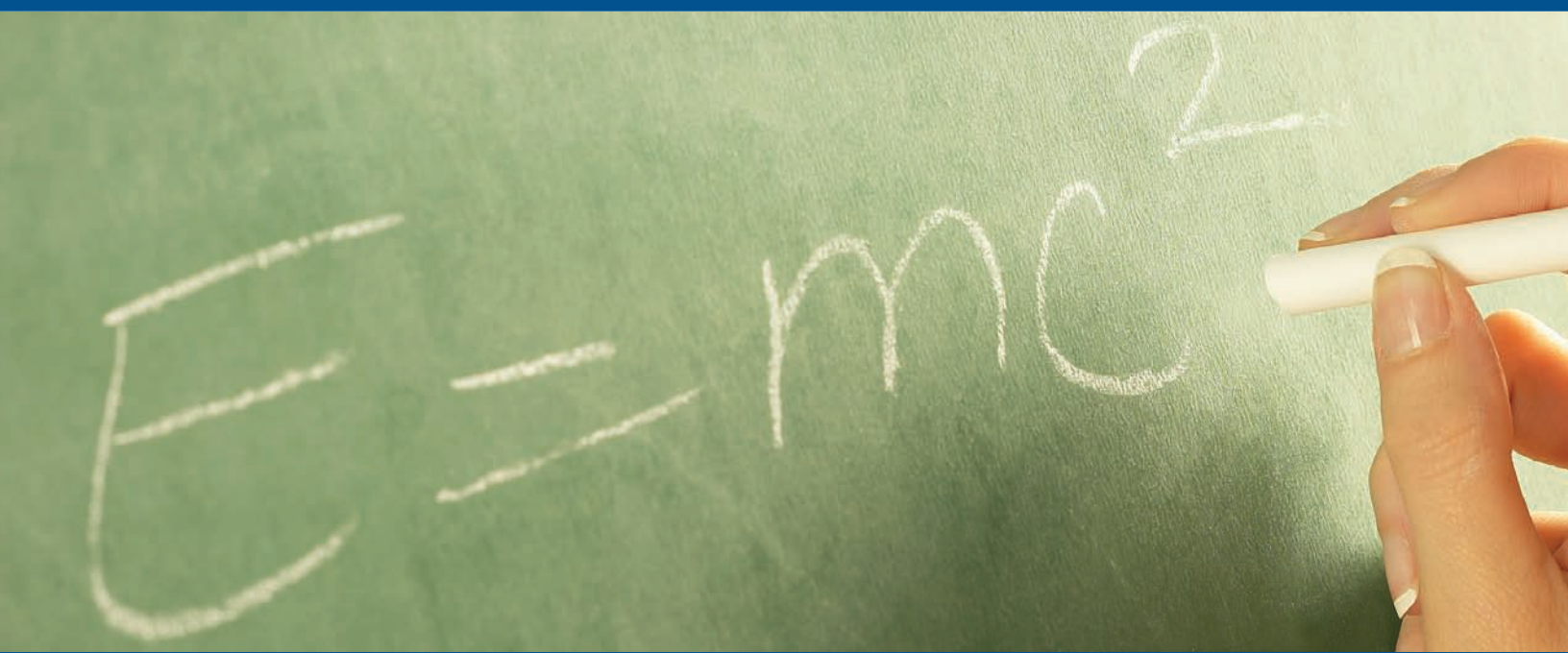


# Report of the Joint AAPT-APS Task Force



American Association of  
**Physics Teachers**



# GRADUATE EDUCATION IN PHYSICS

Revised June 2006

## Committee Membership

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David Campbell, Chair  
*Boston University*

Tom Appelquist  
*Yale University*

Renee Diehl  
*Penn State University*

Joel Fajans  
*University of California, Berkeley*

J.D. Garcia  
*University of Arizona*

Jim Gates  
*University of Maryland*

Allen Goldman  
*University of Minnesota*

Peter Jung  
*University of Ohio*

Michael Paesler  
*North Carolina State*

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## NOTE ON THIS EDITION

This edition replaces the October 2005 publication and contains some minor corrections to data within the narrative as well as corrections to a number of editorial errors. The figures have been revised for clarity of presentation; there were no changes to the data.

## INTERACTIVE FEATURES IN THE PDF

Online Documents and websites mentioned in this report can be accessed directly from this PDF by clicking on any red underlined text. For example, see the Footnotes.

## Executive Summary

The Task Force on Graduate Education in Physics (TFGE), an ad hoc committee convened jointly by the American Association of Physics Teachers (AAPT) and the American Physical Society (APS), has studied the current status of graduate education in physics Ph.D. programs, and has made recommendations based on what was found. The findings indicate that the majority of Ph.D. programs in physics have a common core curriculum and that students must demonstrate mastery of those subjects by passing either courses or exams. The subjects covered in this core curriculum appear to have remained constant, on average, for some time, and most departments do not plan on wholesale changes to their curricula in the near future. Most departments also require some “breadth” courses in different areas of physics. There also appears to be demand from students and potential employers of Ph.D.’s for training in additional skills, such as public speaking, writing, teaching, teamwork, and leadership. The time to Ph.D. has been lengthening slowly over the past 30 years, but many departments are making efforts to curtail the increase (which seems to have succeeded to the extent that there has not been a significant change in time to Ph.D. across the past 10 years). Overall, graduate education in physics appears to be healthy, but departments should be aware that as the fields of physics evolve, flexibility may be an increasingly important characteristic of physics Ph.D. programs.

### **The Task Force’s 16 Recommendations**

This report of the TFGE is best summarized by listing our recommendations, in order of their appearance herein:

1. The TFGE recommends that the content of core courses be consistent year-to-year and be supervised closely by the department. Within that context, the TFGE believes that turnover in instructors is a positive occurrence.
2. The TFGE finds it noteworthy that the two texts that appear to be most widely used, Jackson for Electricity & Magnetism and Goldstein for Classical Mechanics, are also among the oldest books, having been first published in 1962 and 1950, respectively, although the latest editions were published in 1998 and 2002, respectively. We note with some amusement that Amazon.com offers a special price for buying the two together, presumably reflecting the fact that marketers have noticed that many departments indeed use both texts.
3. The TFGE recommends that the Ph.D. physics core curriculum should consist of the material generally covered in a
  - one-year course in Classical Electrodynamics,
  - one-year course in Quantum Mechanics,
  - one-semester course in Classical Mechanics, and
  - one-semester course in Statistical Mechanics and Thermodynamics.
4. The TFGE feels that graduate programs benefit by having some breadth requirement in physics, typically taken within the first two years, and recommends that departments require such breadth. The opportunity to take related courses outside physics is also recommended for many students. Departments should provide opportunities for students to develop other skills, such as machine shop, public speaking, and grant writing.
5. TFGE recommends that departments include attendance at the departmental colloquium as a requirement in their graduate programs. The TFGE also recommends that departments consider adding some required computational training to their graduate programs.
6. The TFGE recommends that departments require communication training and information literacy/fluency in their graduate programs.
7. The TFGE concurs with the APS Task Force on Ethics recommendation that the physics community should sponsor and promote development of ethics education programs, and further recommends that this should occur in graduate programs.
8. The TFGE recommends that department chairs review the “best practices” of their peers in the areas of climate and diversity.
9. The TFGE recommends that departments formulate guidelines for graduate student rights and practices and provide these to graduate students.

- 10.** The TFGE recommends that departments take an active role in monitoring students' progress toward Ph.D., in order to ensure, independent of the advisor, that the student is making appropriate progress.
- 11.** The TFGE recommends that departments offer advice and mentoring to their graduate students on the full range of career options available to physics Ph.D.'s and in particular increase their students' awareness of, and preparation for, positions in industry.
- 12.** The TFGE recommends that department chairs share best practices on a regular basis, both at the biennial meetings organized by AAPT and APS, and on a website.
- 13.** The TFGE recommends that there be continued close collaboration between AAPT and APS on the subject of graduate physics education. The TFGE further recommends that the AAPT/APS periodically reinvestigate the topics studied here, as well as expanding the scope of the studies to obtain a more extensive view of graduate education in physics.
- 14.** The TFGE makes no recommendation at this time concerning the use of comprehensive exams, except to note that there needs to be some method of evaluating students' knowledge of the core subjects.
- 15.** The TFGE recommends that the physics department chairs engage in discussions of comprehensive examinations and their alternatives.
- 16.** The TFGE makes no explicit recommendations concerning specific courses and their content, but we encourage innovative methods for delivering the graduate curriculum.

# I. Introduction

## A. Background and Context

For more than 50 years, physics graduate education in the United States has been one of the crown jewels of our nation's educational system and a significant contributor to the national good. By all measures, U.S. physics education has led the world in attracting and training a cohort of outstanding students and faculty, both domestic and foreign, and in providing a research infrastructure second to none. The contributions to the fundamental knowledge of U.S.-trained or U.S.-employed physicists have garnered the lion's share of Nobel Prizes in Physics, while their advances in applied physics have produced technologies that have strengthened our nation economically and militarily, while improving quality of life through their tremendous contributions to areas such as health care and the Internet.

In the past decade, several events have raised major concerns about different aspects of physics graduate education. First, the debates surrounding the cancellation of the Superconducting Super Collider raised issues of the "factionalization/fractionalization" of physics into noncommunicating (or even hostile!) subdisciplines. Second, throughout the 1990s, the decrease in overall numbers of entering physics graduate students, and the decline in the percentage of domestic students, raised concerns about the future of our physics-trained workforce. Third, the rising quality of the graduate educational programs in many other nations has meant increasing competition for the best students from abroad. Fourth, the increased security concerns following the September 11 terrorist attacks have threatened to greatly restrict our ability to attract foreign students and scholars.

Of course, physics is but one of the critical disciplines needed to maintain U.S. leadership in science and engineering. A recent National Academies Press (NAP) report (*Policy Implications: International Graduate Students and Postdoctoral Scholars in the United States*<sup>1</sup>), released in May 2005, discusses many of these issues in the broader context and concludes, in the words of NAP's press release: "To maintain America's leadership in science and engineering research, a comprehensive effort is needed to improve the recruitment, education, and training of a cross section of U.S. students for careers in these fields—while continuing to attract the most talented scholars worldwide.... These twin goals are critical, given increasing global competition

for top-notch graduate students and researchers." The committee went on to call for "a study to explore which policies and programs would help the United States attract the best international and domestic graduate students and postdoctoral scholars. Providing the highest-quality training and career-development opportunities for these individuals, particularly women and underrepresented minorities, should be the overarching goal of U.S. universities and research institutions."

Essential background for any such prospective study is an understanding of what we are currently doing in graduate education in science and technology. In this report, the TFGGE seeks to provide such an understanding for the specific discipline of physics and to suggest some ways in which we can improve our physics graduate training to respond to the challenges listed above.

## B. Origin of and Charge to the Task Force

In January 2003, AAPT's standing Committee on Graduate Education passed a resolution calling for the formation of a task force to study the status of graduate education in physics in the United States. The resolution was passed partly in response to discussions concerning the fractionalization of physics as a discipline and the factionalization of physics as a community, which were raised by Sid Nagel in an opinion piece published in *Physics Today*, September 2002.<sup>2</sup> A concern was expressed that the graduate curriculum might have changed in ways that would weaken the "unity" of physics as a discipline (e.g., fewer common courses required, lowering the level of the comprehensive exam), but no extensive data were available to test this perception.

Other factors contributed to the decision to pass the resolution, including the observation that while the content of the curriculum (graduate and undergraduate) for other science subjects, notably biology and chemistry, have changed remarkably in the past 20 years, the content of the physics curriculum appears to have changed little in the past 50 years. In addition, the advent of some high-profile cases involving ethics in physics research raised questions concerning whether physics educators are failing to provide important sectors of training to their students.

Thus, the resolution that was passed recommended the formation of a task force that would study the current status of graduate education in physics, with a view toward

modernization of the curriculum. Further, the resolution stated that the task force should be composed of people who are involved in and knowledgeable about graduate education curricula.

In discussions of the Executive Board of AAPT and the Committee on Education (COE) of APS, it was agreed that the TFGE should be jointly sponsored and staffed by AAPT and APS. It was further decided that the TFGE should consist of nine members, three appointed by AAPT, three by APS, and three jointly appointed. The charge to the TFGE, developed by Charlie Holbrow and Judy Franz, broadly asked the TFGE to examine the current status and recent evolution of graduate education in physics and to make recommendations to improve it:

“The AAPT-APS Joint Task Force on Graduate Education will examine and summarize directions in graduate education in physics as it has evolved over the past 10 years with special emphasis on doctoral programs. The Task Force will identify special challenges and problems facing graduate education in physics and recommend actions for the two organizations and/or Ph.D.-granting universities to take in response to these issues. In performing its charge, the task force should make itself aware of the results of past studies of graduate education in physics.

“Because of concerns that Ph.D. education is becoming too narrow, the task force should suggest positive steps to help graduate students learn physics that will enhance their understanding of the interconnections between different fields, prepare them to apply physics in a variety of fields or disciplines, foster their appreciation of the breadth of physics, and stimulate them to become aware of the diverse contributions that physicists make.”

The following specific points were identified as elements that should be considered in the work of the TFGE:

- ▲ **The Current Status of Graduate Education** – the key elements of Ph.D. programs, graduate course content, specialization courses vs. common core courses, curriculum for students in interdisciplinary fields, how the mastery of the subject is measured.
- ▲ **The Graduate Student Experience** – the length of time to Ph.D., time spent on coursework vs. research,

comprehensive/candidacy/qualifying exams, communication skills, information literacy, ethics, training, rights.

- ▲ **Departmental Issues** – recruiting, financial support and benefits, career guidance, diversity, balance of foreign and domestic students, climate.

### C. Approach of the TFGE

The task force first met by conference call in March 2004, and decisions were made regarding the approach to the project. Although some data existed from earlier surveys (see below), much of the specific information described above did not exist. The TFGE decided that new surveys would be the best way to obtain the required new data on current graduate programs and their recent history. The Statistical Research Center of AIP agreed to help to create, administer, and analyze a new survey to all physics departments with doctoral programs in physics. In view of the centrality of this survey, the final report based on it is now available on the AIP website: “Core and Breadth in Physics Doctoral Education.”<sup>3</sup> In addition, leaders of the APS Forum on Graduate Student Affairs (FGSA) conducted a survey of its members and gleaned valuable anecdotal comments that are included in this report. The purpose of the new AIP survey was to assess the diverse aspects of doctoral education in physics, with an emphasis on the extent to which physics departments require Ph.D. students to master a core physics curriculum. Respondents completed the survey online, after receiving an email request sent to all Ph.D.-granting physics departments in the United States. Of the total 186 Ph.D.-granting physics departments, 114 answered online. Additional information on graduate programs for 23 nonresponding physics departments was obtained in web searches, for a total of 137 departments. These departments enrolled 76% of all doctoral students in physics. The FGSA survey consisted of 13 questions inspired by the mission statement of the TFGE. The FGSA has about 1,000 members, mostly graduate students, with some postdoctoral fellows. About 50 responses were obtained, all from current graduate students in physics and applied mathematics. Each question had at least 20 responses.

The data acquired from the new surveys were combined with findings of existing surveys, reports, publications, and input from various groups to inform the TFGE of the current status of graduate education and as a basis for recom-

mendations. The complete list of reports and groups consulted includes:

- AIP survey of departments with Ph.D. programs in physics “Core and Depth in the Doctoral Physics Program,” 2004
- Survey of APS Forum on Graduate Student Affairs, 2004
- APS Committee on Education
- AAPT Committee on Graduate Education
- APS Forum on Industrial and Applied Physics
- AIP Graduate Student Report (October 2004)
- AIP Initial Employment Report (2000)
- National Science Foundation Reports on Graduate Education in Physics
- APS Task Force on Ethics surveys to department chairs and recent Ph.D.’s (2004)
- National Academy of Science report on “Reshaping Graduate Education”
- American Association of Colleges and Universities’ report on graduate education
- 1995 Physics Department Chairs Meeting report, “Physics Graduate Education for Diverse Career Options”
- *Careers in Science and Engineering*, National Academy Press, 1996
- *A Ph.D. Is Not Enough* by P. J. Feibelman, Perseus Books Group, 1994
- *Integrating Information Literacy into the Higher Education Curriculum* by I.F. Rockman, Jossey-Bass, 2004

The following data from existing surveys provided a helpful starting point for framing some of the issues to be addressed in this report. Figure 1 shows the number of first-year physics and astronomy graduate students over roughly the past 40 years. The sharp downward trend of the early 1990s is clearly visible, as is the partial recovery during the past few years.

Figure 2, which presents the median time to Ph.D. and the median age at receipt of Ph.D. for roughly the past three decades, shows an increase of about one year in the median time to Ph.D. (from ~6 years to ~7 years) but an increase of nearly two years (from 30 to 32) in the median age at receipt of Ph.D. The distribution of length of time

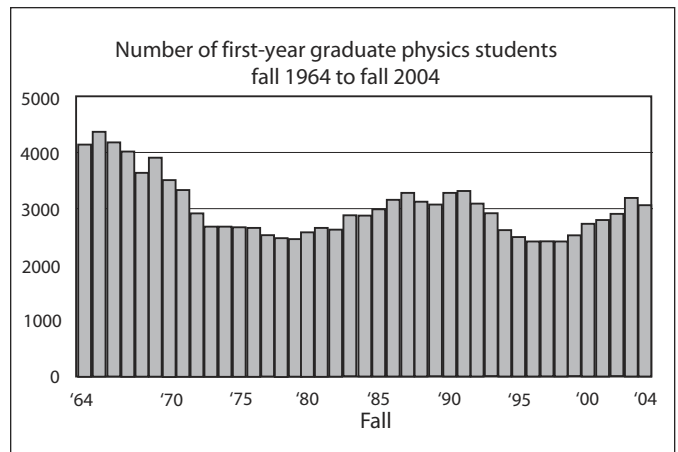


Figure 1. Number of first-year physics and astronomy students 1964–2004, from AIP Survey of Enrollments and Degrees.

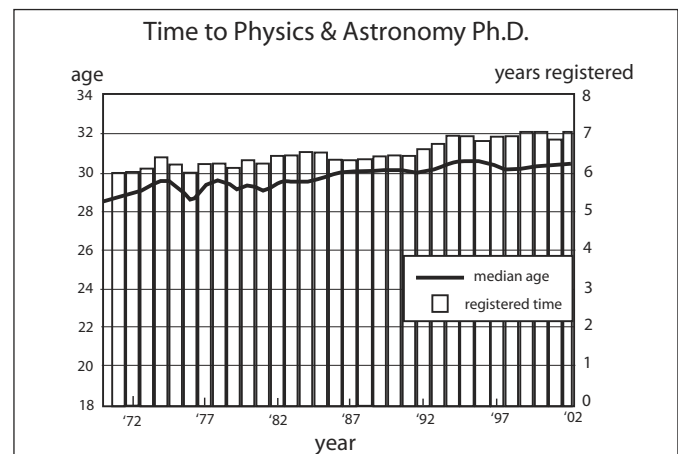


Figure 2. Median time to Ph.D. and median age at receipt of Ph.D. for 1972–2002, from the National Science Foundation Division of Science Resources Statistics.

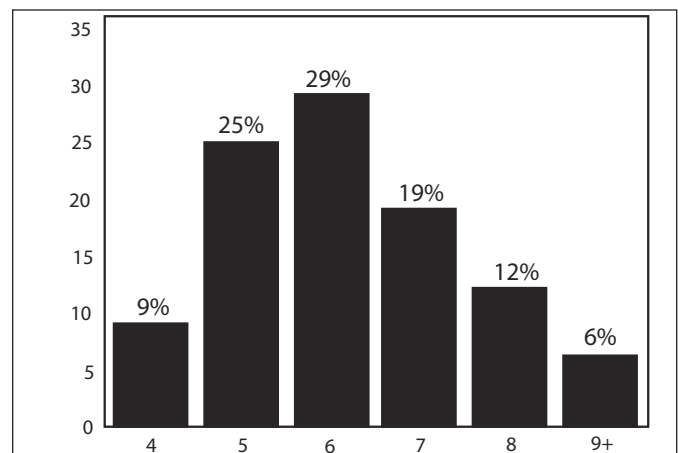
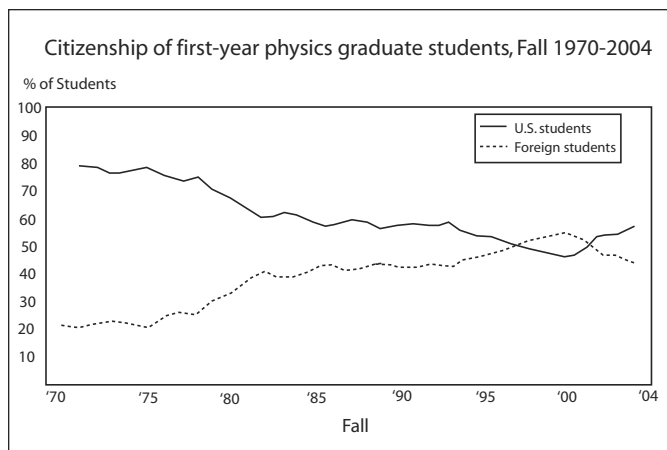


Figure 3. The number of full-time equivalent years of graduate study completed by the Ph.D. class of 2000, from the AIP Statistical Research Center, Initial Employment Report.



**Figure 4. Citizenship of first-year physics and astronomy graduate students, 1971-2003, from the Survey of Enrollments and Degrees of the AIP Statistical Research Center.**

to Ph.D. is shown in Figure 3 for the Ph.D. class of 2000. It shows that 63% of the students received their Ph.D.'s in six years or fewer.

Figure 4 shows the citizenship of first-year physics and astronomy graduate students over roughly the past three decades. The trends mentioned in the introduction are clear, as is the dramatic increase in the percentage of foreign students from 1970 to 1983. The downward trend after 2001 is caused partly by the response of the U.S. government and the foreign students following the September 11 attacks. However, there was also a large increase in the enrollment of U.S. students in graduate physics programs during that period.

## II. The Graduate Physics Curriculum

### A. The Existing “Core”

The traditional (historical) graduate physics curriculum consists of a “core” of required courses that includes Classical Electrodynamics, Quantum Mechanics, Classical Mechanics, and Statistical Mechanics. Anecdotal evidence suggests that some graduate physics departments have changed or eliminated these requirements, or made other changes such as the elimination or “watering down” of the comprehensive exam. It also has been argued that physics departments need to modernize the curriculum, noting that the traditional core has not changed for 50 years.

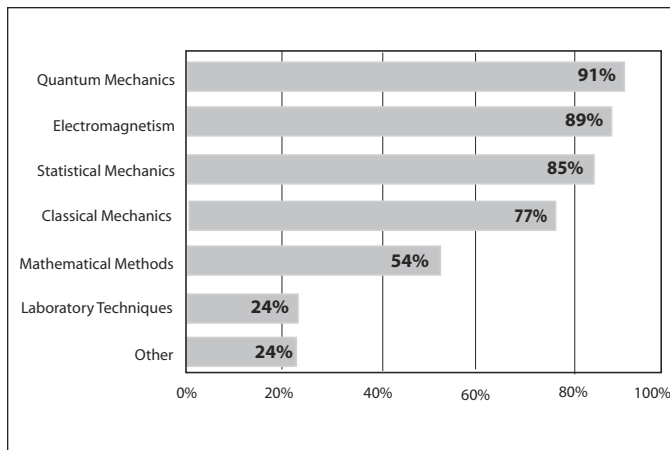
Whether changes to the graduate curriculum indeed have occurred is difficult to assess because, to our knowledge, there has never been a survey to determine the status of the graduate physics curriculum. Therefore, the TFGE commissioned the AIP in 2004 to assess the current status and recent changes to the physics curriculum. Their report, “Core and Depth in Physics Doctoral Education,” was based on a survey of the 186 physics departments that have doctoral programs in physics.<sup>3</sup> The survey solicited information on the current graduate program as well as recent and expected changes. This section also includes results obtained from a survey of the APS Forum on Graduate Student Affairs (FGSA).

For the purposes of the AIP survey, traditional core courses were defined as Quantum Mechanics, Statistical Mechanics, Classical Mechanics, and Classical Electrodynamics. Of 137 departments, 129 were found to require some traditional core courses. There were eight departments that do not require any of the core courses, and five that do not require the traditional core but do require lab techniques or math methods. However, these 13 departments do require students to pass an exam on the traditional core course material.

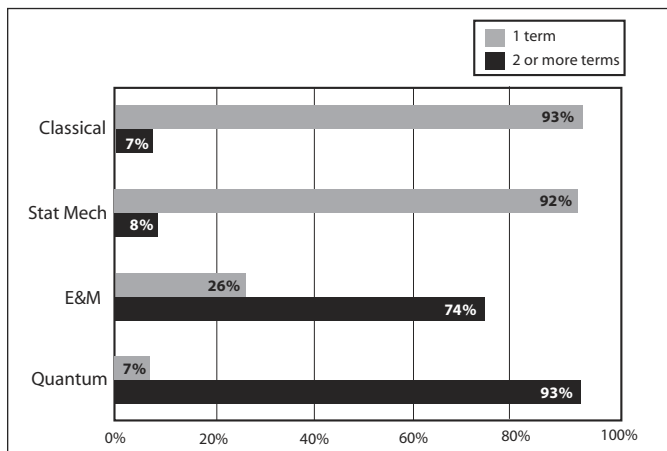
To address the consistency of the core curriculum, questions were asked about how often instructors of these courses changed and whether the content of the course changed significantly when the instructors changed. About a quarter of departments indicated that the same instructor had taught a core course for at least three years, but fewer indicated that the content of the course changed when the instructor changed.

The TFGE recommends that the content of core courses be consistent year-to-year and be supervised closely by the department. Within that context, the TFGE believes that turnover in instructors is a good thing.

The consistency of the curriculum across the surveyed departments was measured by recording which textbooks were used. Although many different texts were used in the core courses, a surprising number of departments reported using the same text. Of the 80 departments responding, 76 use Jackson for Electricity & Magnetism, and 48 use Goldstein for Classical Mechanics. There was more variation in the books cited for Quantum Mechanics, with 26 (out of 74) indicating that they use Sakurai’s *Modern Quantum Mechanics*, 18 indicating Shankar’s *Principles of Quantum Mechanics*, 14 indicating Cohen-Tannoudji et al.’s *Quantum*



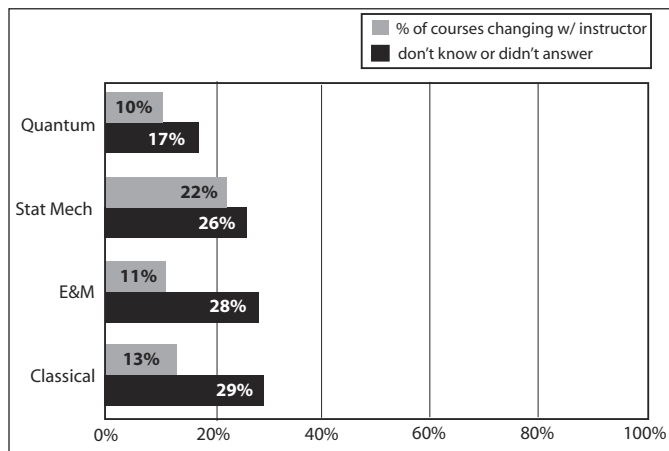
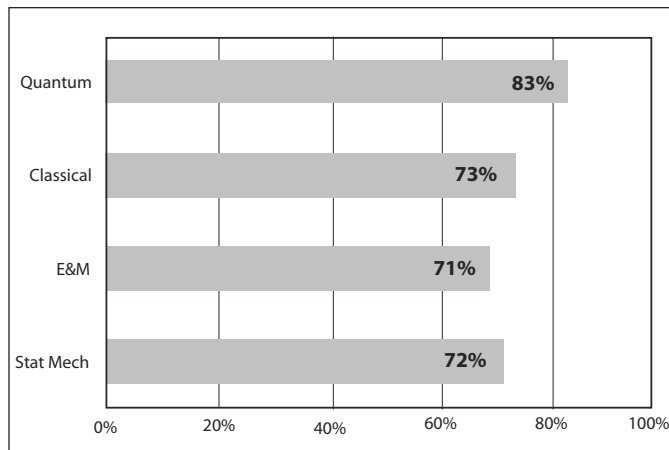
**Figure 5.** The distribution of required courses in the 137 departments for which we have data. The “other” category includes Advanced Topics, Astronomy, Computational Physics, Elementary Particle Physics, Introductory Astrophysics, and Modern Physics.



**Figure 6.** Number of terms or semesters of the core courses required. Sixteen percent of these departments required three or more terms of Quantum Mechanics.

*Mechanics, Vol 1.*, and 11 indicating Merzbacher’s *Quantum Mechanics*. For Statistical Mechanics, 26 (out of 65) indicated that they use Pathria’s *Statistical Mechanics* and 13 indicated Huang’s *Statistical Mechanics*. Some departments cited using more than one text for the courses. (See footnote 3 for more data on textbook usage.)

The TFGE finds it noteworthy that the two texts that appear to be most widely used, Jackson for *Classic Electromagnetism* and Goldstein for *Classical Mechanics*, are also among the oldest books, having been first published in 1962 and 1950, respectively. The most recent editions were



**Figure 7.** Percentage of core courses changing instructor during the past three years (top), and percentage where the material is significantly different when different instructors teach the course (bottom).

published in 1998 and 2002, respectively. We note with some amusement that Amazon.com offers a special price for buying the two together, presumably reflecting the fact that marketers have noticed that many departments indeed use both texts.

Of the 98 departments that responded to this question, 68 had at least one student studying in an interdisciplinary program. Ninety percent of those with interdisciplinary students require all students, including interdisciplinary students, to take the core courses, while 6% reduce the core requirements for interdisciplinary students, and 4% simply have no core course requirements.

As another point of interest, the FGSA survey asked current graduate students which undergraduate courses should have been part of their undergraduate major, and the re-

sponses indicated that there should have been more physics, mathematics, laboratory, and computer courses.

## B. Comprehensive/Qualifying Exam

Although not every department requires that students take the core courses, all of those that do not still require that students demonstrate a mastery of this material by passing an exam. Most departments required that students pass such an exam in addition to the core courses. Out of 124 departments, 107 require a comprehensive type exam. Six percent of departments have an oral exam, while the rest are written, or combined written and oral. Most (64%) require students to pass it by the end of their second year or earlier. And most departments (73%) allow the students two tries to pass the exam. The topics covered for most departments were those of the core courses (90% covered quantum mechanics and classical electrodynamics, 86% covered classical mechanics, 75% included statistical mechanics). Thirty-two percent of the departments also included math methods, 11% included laboratory techniques, and 37% included other topics. The level of the exam was a combination of undergraduate and graduate material in most (57 out of 84) departments, while 15 departments covered only graduate material and 14 departments covered only undergraduate material.

## C. Recent Changes to the Core

The AIP survey found that 32 of the 96 responding departments either increased (9) or decreased (17) or both increased and decreased (6) their required core courses in the past five years. Eight departments responded that they changed the number but did not specify if it was an increase or decrease. Fifty-six departments reported no changes in course requirements; however, one third of those said that discussions are currently being held about changing requirements.

### Dropping or decreasing required courses

Departments reported 32 changes in different courses. Nearly half of the changes involved reducing by one the number of terms that students had to complete a required course. About one-third of the comments referred to changing a previously required course into an optional one. Sev-

eral of the latter noted that the optional course was made into a prerequisite to be taken by students who had not covered the same material as undergraduates. There were only five comments that indicated that a formally required course was dropped entirely and, in most of these cases, the material was moved to other courses. Finally, only two comments indicated that a formally required course was replaced with a new required course.

The most common reasons given for decreasing the required courses were related to reducing the time students spend on the core courses and facilitating taking specialized courses. Of the 23 departments that described dropping or reducing required courses, about half noted a change in Classical Mechanics and nearly half noted Mathematical Methods.

The reasons given for *decreasing Classical Electrodynamics* were:

- Two-semester course was condensed into one.
- Dropped one semester and taught advanced topics in another course when needed.
- Changed from a classical Jackson approach to an applied optics approach.
- The advanced material will be offered in introductory sections of advanced courses.
- The course became optional to allow students more flexibility in setting up their programs.
- Replaced Classical Electrodynamics with Math Methods.

The reasons given for *decreasing Math Methods* were:

- The second semester was made optional.
- This course was made an elective to decrease the number of required courses.
- The course was deemed to be too specialized.
- Determined that the key points could be covered in one semester.
- Reduced requirement to allow students into research earlier.
- Decided well-prepared students should not be required to take it.
- Core was deemed to be too big.
- Advanced topics were moved to an advanced course.
- Made the course an elective because it is taught by another department.

The reasons given for *decreasing Statistical Mechanics* were:

- Reduced the course to one semester to shorten time for required courses.
- Made second semester optional to enable more specialization courses.
- Want students to move into research earlier.
- Completion of core in one year is desirable, move to advanced course.

The reasons given for *decreasing Classical Mechanics* were:

- Required semesters reduced to make it easier to complete courses earlier.
- Made second semester optional in order to enable more specialization courses.
- Made optional to allow more flexibility in programs of study.
- Course was not very useful.
- Advanced topics were moved to an advanced course.

### Adding or increasing required courses

Fifteen departments provided comments that described additions to their required courses. Nine comments indicated that their comprehensive exam was being replaced by a requirement that students pass specific core courses. Six comments referred to requiring students to take a course that had formerly been optional, largely as a result of concerns about undergraduate preparation. Three comments referred to increasing the number of terms that students were required to take a specific course by one. Of the departments that described adding or increasing required courses, nearly half noted a change in Quantum Mechanics.

The reasons given for *increasing Quantum Mechanics* were:

- The course replaces a qualifying exam.
- An introductory course was added to the sequence.
- A second semester is now required instead of being optional.

The reasons given for *increasing Classical Electrodynamics* were:

- For astronomers only.
- The course replaces a qualifying exam.

The reasons given for *increasing Mathematical Methods* were:

- Poor preparation among incoming students.

- Replaced Electrostatics with a broader course in Math Methods.

The TFGE recommends that the Ph.D. physics core curriculum should consist of the material generally covered in a:

- one-year course in Electricity & Magnetism,
- one-year course in Quantum Mechanics,
- one-semester course in Classical Mechanics, and
- one-semester course in Statistical Mechanics & Thermodynamics.

The core courses must prepare students for careers in which they will be expected to solve problems that have not been solved or possibly even addressed before. Hence they must be taught how to formulate problems from basic principles.

In the core course Electricity & Magnetism, students should be taught how to synthesize the basic tools (Maxwell's Equations, special relativity, mathematical theorems, orthogonal-function expansions, transformations from microscopic parameters to macroscopic observables, etc.) to establish general approaches. This preparation will allow them to describe and understand from first principles such interesting phenomena as negative refractive index materials, nonlinear optics, short-pulse propagation, and nanostructured materials.

The core course on Quantum Mechanics similarly must establish fundamental concepts and formulations of the quantum world. For example, foundations must be built and skills developed in using vector spaces, operators, representations, and variational and perturbational methods. Paradigmatic models such as particles in harmonic wells and central potentials, angular momentum and spin systems, many-body systems, and symmetries should be included. The approach should prepare students to address the novel and emerging quantum mechanical problems they will confront as professional physicists in their studies of condensed matter, optics, nuclear physics, high energy physics, etc.

Comparable core mastery in Classical Mechanics and in Statistical Mechanics & Thermodynamics would complete a Ph.D. candidate's core preparation. Core mastery is attained when one can solve problems involving physical situations typically discussed in such courses through application of the principles presented in the courses.

### **D. Core Requirements in the “Top 30” Ph.D. Physics Programs**

Because of anecdotal evidence that the highest-ranking physics departments have fewer requirements in terms of coursework and/or comprehensive exams, the data from the aforementioned AIP “Core and Depth in Physics Doctoral Education Survey” were separated into the “top 30” departments and the “rest.” The “top 30” were identified by their rankings in the latest NRC ranking, and the survey includes data from 29 of them. All of these departments require core courses, a comprehensive exam, or both. Specifically, eight departments require the comprehensive exam but none of the four courses defined as “core” here. Seven require at least three core courses but have no comprehensive exam. Only 14 (just under 50%) require both core courses and the comprehensive exam, whereas 80% of the “rest” of departments require both.

Of those that require core courses, Classical Mechanics is the least likely to be required. About 50% of the “top 29” departments surveyed require this course, compared with more than 75% of the rest of the departments.

### **E. Breadth**

Students normally take advanced courses in their area of specialization, and some departments also require that they take courses outside their specialization. The AIP survey found that of the 111 physics departments who responded, 48% do not require students to take any courses outside their specialization, and 52% require at least one course.

When asked to specify their best practices as a department, 32 departments cited their efforts to include breadth in their graduate curricula. Most departments indicated that they required a fixed number of courses beyond the core courses. In some departments, students were free to choose from those offered. Others had a similar policy but specified that some number of these courses should be different from their specialized field. A few departments specified or included courses outside the physics department, such as graduate mathematics courses.

One way of developing a broader perspective in physics is through attendance of colloquium. Of the 99 departments responding, 34% require their graduate students to attend colloquium but do not assess it, while 15% require attendance and do assess it. Fifty percent encourage but do

not require their graduate students to attend colloquium, while 1% of departments did not encourage it.

The FGSA survey asked students what distribution courses (outside their chosen subfield) were required and whether they found them useful. Most students found these to be useful as long as they were kept general and didn’t add too many hours to their workloads. Some stated that colloquia were more understandable after having taken distribution courses. There was considerable interest in distribution courses outside of physics: in engineering or mathematics.

The students were also asked which undergraduate courses in other disciplines were or would have been helpful. Mathematics, computer programming, chemistry, and machine shop were mentioned as courses that were or would have been useful. Students also felt that training in “life skills” such as grant writing, public speaking, and how to find a job would be helpful in their undergraduate training.

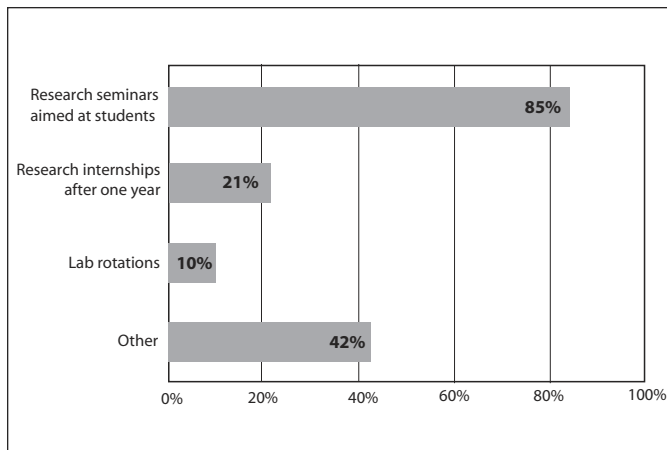
Clearly, distribution requirements within physics are common and are considered to be useful by both departments and students. The TFGE feels that graduate programs benefit by having some breadth requirement in physics, typically taken within the first two years, and recommends that departments require such breadth. The opportunity to take related courses outside physics is also recommended for many students. Departments should provide opportunities for students to develop other skills, such as machine shop, public speaking, and grant writing.

TFGE recommends that departments include attendance at the departmental colloquium as a requirement in their graduate programs. The TFGE also recommends that departments require computational training in their graduate programs.

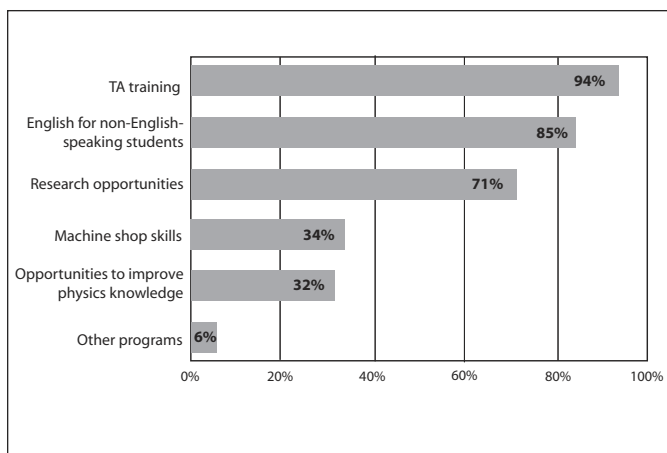
## **III. Beyond the Curriculum: The Total Graduate Student Experience**

### **A. Mentoring and Additional Training of Graduate Students**

Departments were asked how they provide assistance to students *in choosing a research area*. Figure 8 shows the response to this question. Most departments used research seminars to provide information on research fields and op-



**Figure 8. Methods used by departments to assist students in choosing a research field. Percentages do not sum to 100% because departments could choose all that applied. "Other" includes discussions with faculty, graduate seminars introducing faculty research, poster sessions, and summer fellowships.**



**Figure 9. Programs offered to first-year graduate students. Percentages do not sum to 100% because departments could choose all that applied. Other includes research seminars or summer research.**

portunities, but some provided other means, such as lab rotations, research internships, and graduate seminars to introduce faculty research, poster sessions, and summer fellowships. Figure 9 indicates what other programs are offered to first-year graduate students. Several departments indicated that their remedial training for ill-prepared graduate students was one of their best practices for the success of their graduate program.

The graduate students who responded to the FGSA survey indicated that *training in teaching* is an important issue. Most students agreed that training and the experience of

teaching was important and many students expressed interest in receiving more training. Six departments cited their TA training courses as one of their “best practices.”

Only two departments in the AIP survey volunteered that they provide explicit *communication training* to their graduate students, although such training was cited by a recent Academy of Sciences survey (“Careers in Science and Engineering: A Student Planning Guide to Grad School and Beyond”) as being particularly important. That report recommended taking communication skills classes in scientific writing or speech, joining the Toastmaster’s Club, or volunteering to talk about your specialty to local civic groups or high school classes. Also recommended was peer training where graduate students should form a cooperative group, make presentations to each other, and agree to provide (and accept) honest responses.

*Information fluency* is a subject that has garnered increasing attention in other subjects such as chemistry and the life sciences, and particularly in health-related fields, because of an increasing number of information and liability issues.<sup>4</sup> The ability to find and evaluate information is crucial in the decision-making process. In physics, “knowing the literature” is an increasingly complex undertaking, and has significant implications for efficient use of research funds, and can raise questions concerning professional ethics (see below).

The TFGE recommends that departments require communication training and information literacy/fluency in their graduate programs.

## B. Ethics

The AIP survey asked departments if they provided ethics training to their graduate students. This question was timely because there were several other recent ethics surveys and a report from the APS Task Force on Ethics was published in the November 2004 *Physics Today*.<sup>5</sup> This report included a survey of recent (less than three years) Ph.D.’s in physics and had 748 responses. It indicated that while 81% of students are aware of the APS ethics statement (see box on next page), less than 10% had formal ethics training as graduate students (the most common method of learning about ethics was from discussions with colleagues). Thirty-nine percent of the respondents had a personal knowledge of ethics violations—mostly data falsification and treat-

ment of subordinates—and 62% commented that the APS statement should be broadened to include the treatment of subordinates.

### **The APS Statement on Improving Education for Professional Ethics, Standards, and Practices**

Education in professional ethics and in practices that guarantee the integrity of data and its analysis are an essential part of the ongoing training of scientists. It is part of the responsibility of all scientists to ensure that all their students receive training that specifically addressed this area. The American Physical Society calls on its members and units to actively promote education in this area and will sponsor symposia on professional ethics, standards, and practices at its general meetings.

The APS Task Force on Ethics made several recommendations, including “The Physics Community should sponsor and promote development of ethics education programs.”

The responses to the AIP survey indicated that

- 66% of departments do not provide ethics training.
- 25% provide it through the university.
- 7% provide it in the department.

Descriptions of ethics training included taking ethics courses, workshops, independent study, lectures, reading written material, and informal training. Of the 31 universities that offer ethics training, 71% do not require it.

A survey to department chairs was also carried out by the APS Task Force on Ethics. Of the department chairs surveyed, only 33% were from Ph.D.-granting universities. The results of this survey indicated a somewhat higher degree of ethics training than that suggested by the AIP survey.

In particular,

- 47% have discussed ethics more than casually in the past two years.
- 46% have incorporated ethics issues in graduate/undergraduate seminars.
- 75% have incorporated ethics issues into lab courses.
- 7% estimate that faculty engage in ethics discussions with graduate students frequently.
- 30% estimate that faculty engage in ethics discus-

sions with graduate students one to three times per year.

- 38% estimate that faculty engage in ethics discussions with graduate students seldom if ever.

Again, the most common ethics violations observed involved data falsification and treatment of subordinates. Strong feelings were expressed by some department chairs concerning the ethos in physics research promoting “flashy” research as being behind many lapses in ethics.

In the FGSA survey, most student respondents felt that ethics were learned at home at a young age and couldn’t be taught in a formal course. However, they indicated that they learned scientific ethics from their advisor and other scientists, mostly by example. Some students mentioned the APS session at the 2003 March Meeting, the ethics column in APS news, seminars at REU programs, and reading *Nature and Science*, where authorship and other ethical issues are discussed. Students thought that an occasional meeting to discuss these issues could be helpful.

The TFGE concurs with the APS Task Force on Ethics recommendation that the physics community should sponsor and promote development of ethics education programs, and further recommends that this should occur in graduate programs.

## **C. Climate and Community**

According to the TFGE survey, the vast majority of graduate students stated that *the building of community* in a physics department is important to them. They indicated that a centrally located graduate student lounge is beneficial; whereas decentralized offices and departments or research groups being spread out over the campus are detrimental to a feeling of community.

Twenty-eight departments cited their efforts to increase diversity as one of their best practices, while seven cited their efforts at improving departmental climate. Some mentioned their collegial atmosphere or a focus on the student’s needs:

- “Retain flexibility in tailoring the student’s program to their needs, so as to maximize the student’s chance of successful completion of the Ph.D.”
- “We have a small individualized program that has a very high success rate.”

Some also mentioned extensive and successful efforts to recruit and retain women and minorities: “This year 50% of our incoming class was female! We do a great job of supporting women and minorities.”

The TFGE recommends that department chairs review the “best practices” of their peers in the areas of climate and diversity.

An issue that is of paramount importance to students is their *rights*. The FGSA survey indicated that graduate students consider their rights to include salary, health care, leave of absence, ability to retake exams, freedom from harassment, and intellectual property ownership. Some students suggested unions as a means of securing and protecting rights as well as establishing national standards with regard to salaries and benefits. Others said that lobbying of departments and universities by the APS would be better. There were concerns about low salaries and expensive health care, especially with regard to children. Some students suggested that graduate students receive the same benefits that staff members receive. Another suggestion by students was to require universities and/or research grants to specify student rights concerning salary, benefits, workload, and reimbursement for travel to conferences.

With regard to graduate student stipends, the TFGE calls attention to a report of the U.S. Senate Budget Committee, as quoted by AIP FYI in 2001.<sup>6</sup> The report indicated in part:

“Increasing stipends within the NSF graduate education programs is one strategy to attract more U.S. citizens to graduate education in science and engineering. Currently, the average stipend level for graduate education in science and engineering is less than half the average wage for bachelor’s degree recipients. This wide disparity may be a significant factor in declining graduate school enrollments for science and engineering. A recent survey found that 57% of baccalaureate recipients did not apply to science and engineering graduate programs for financial reasons. This is particularly true for under-represented minorities. Therefore, the Committee has increased the graduate education subactivity request by \$15,000,000. These additional funds are to be used to increase the stipends for graduate students by nearly 20% to a level of \$21,500.”

We note that the level for NSF fellowships is now \$30,000 and recommend that departmental teaching fellowships and research assistantships should be moved to levels consistent with the NSF-funded predoctoral fellowships.

Many universities already have policies and guidelines concerning workforce issues, but other issues such as vacation time and conference attendance are often at the discretion of the faculty advisers. It may be useful to establish departmental norms and expectations for such matters. The character of such norms should be a subject of discussion among the physics department chairs.

The TFGE recommends that departments formulate guidelines for graduate student rights and practices and provide these to graduate students.

Conference attendance is an important part of graduate education. Most respondents to the FGSA survey attended zero, one, or two conferences with a few attending as many as five. Lack of funding for attending conferences was cited as a concern.

#### **D. Time to Ph.D.**

The monitoring and training of graduate students has an impact on the total time to graduation, and departments were asked how they monitor the progress of advanced graduate students. Most departments (80%) expect the faculty to discuss progress with their students. Fifty-seven percent use an annual formal assessment of progress toward Ph.D., while 19% use other forms of monitoring such as meetings with their committee, student-submitted progress reports, and meetings with the graduate coordinator. Two percent of departments do not monitor graduate student progress. When asked to cite their best practices as a department, 26 departments felt that their mentoring of graduate students was particularly effective, with most citing personal and frequent interaction between faculty and students. Thirty departments felt they were outstanding in maintaining a respectable average time to degree.

In the FGSA survey, the students were asked the typical number of years to the Ph.D. in physics and whether they thought that it was a reasonable time. The typical number cited as reasonable was five to six years, with the lowest four, and an upper limit of eight to nine. The eight- to nine-year time was not thought to be reasonable for obvious

reasons relating to life style and economics. Students said that regular meetings with their advisor along with honest advice from advisors and committee members were needed to speed the time to degree. They suggested that professors should be discouraged from holding on to students for too long and that departments should have short-term deadlines to help keep students on track.

The TFGE recommends that departments take an active role in monitoring students' progress toward their Ph.D. in order to ensure, independent of the advisor, that the student is making appropriate progress.

## IV. Potential Employers' Views of Graduate Training

According to the 2004 AIP Graduate Student Report, most Ph.D. students aspire to work in an academic setting (70%), with most of the rest indicating they would like to work in industry or government labs.

Members of the APS Forum on Industrial and Applied Physics were consulted on their perceptions of the training of Ph.D.'s in physics. They broadly stated that current physics curricula are training physicists in ways that are beneficial for employment in industry. The following specific points were made:

- When physicists work in industry, there is often a dilemma because Ph.D. physicists are trained to understand a topic deeply, but many instances in industry do not require such depth, and indeed, do not warrant it.
- More options that allow students to pursue breadth over depth would be desirable in many cases. However, a Ph.D. with all breadth and no depth offers no advantage over a typical M.S. degree in a typical industrial hiring situation.
- Emphasis on teamwork, communication, use of concepts in applications, and real-world problem solving would be beneficial.
- Most faculty members could benefit from the type of supervisory training that is common in industry: e.g., learning how to listen effectively and to give honest and constructive feedback while valuing diversity.

- Cross-disciplinary seminar series run by students provide good training for industry.
- Instruction in skill building—communication, interpersonal skills, networking, email, time management, etc.—is very helpful.

The FGSA survey indicated that students get career advice from their advisors and other scientists, especially for academic career track advice. But many students felt pressure to stay in academia and found it difficult to find information on nonacademic careers.

The TFGE recommends that departments offer advice and mentoring to their graduate students on the full range of career options available to physics Ph.D.'s and in particular increase their students' awareness of, and preparation for, positions in industry.

## V. Departmental Best Practices

The AIP survey asked the department chairs to identify the best features of their graduate programs, and 74 responded. The responses are reproduced verbatim in the aforementioned NAP Report. Several themes were common among the responses. These included:

- The reduction or elimination of required core courses in order to allow students to obtain a broader understanding of physics.
- Initiating and/or facilitating interdisciplinary programs of study.
- Focusing the research subject offerings within (smaller) departments.
- Recruiting efforts to increase the numbers of women and/or minority students.
- Starting the research experience for students early as a mechanism for retention and to reduce the time to Ph.D.
- Careful and frequent mentoring and advising of graduate students.
- Promoting and fostering a collegial atmosphere within the departments or groups, and encouraging close interactions among students.

The TFGE recommends that department chairs share best practices on a regular basis, both at the biennial chairs meetings organized by AAPT and APS, and on a website.

## VI. Toward the Future

The absence of earlier comprehensive surveys of graduate programs implies that we cannot accurately assess how graduate programs in physics have changed in the past 10, 20, or 50 years. However, this report represents the first quantitative and comprehensive survey of Physics Ph.D. programs and provides a description of them as of the time of our survey (2004). To ensure that any future studies are properly informed, the TFGE recommends that there be continued close collaboration between AAPT and APS on the subject of graduate physics education. The TFGE further recommends that AAPT and APS periodically reinvestigate the topics studied here and expand the scope of the studies to obtain a more extensive view of graduate education in physics.

A primary charge to the TFGE was to examine the current status of graduate education in physics and to make recommendations for its improvement. Because the focus of the charge was Ph.D. programs in physics, the TFGE did not address master's degree programs or the award of master's degrees to students in Ph.D.-granting departments. We also did not investigate or evaluate differences that may exist between departments that are physics only and ones that are physics and astronomy. Our focus on *nature* and *content* of the graduate program meant that we did not directly address issues concerning either graduate enrollment or the criteria used for admission to the graduate programs.

Qualifying or comprehensive exams are a memorable and defining experience for many graduate students in physics, although they are not ubiquitous. There are indications in the comments made by respondents of the survey that some departments are experimenting with replacing some course requirements with exam requirements, while others are replacing exam requirements with additional (usually breadth) courses. The majority of departments in-

clude both graduate and undergraduate material in these exams. As mentioned in the introduction, there is anecdotal evidence that the level of the exams may be lower than it once was, but there are no earlier data for comparison. Given this level of variation and uncertainty, the TFGE makes no recommendation at this time concerning the use of comprehensive exams, except to note that there needs to be some method of evaluating students' knowledge of the core subjects. The TFGE recommends that the physics department chairs engage in discussions of comprehensive examinations and their alternatives.

The TFGE makes no explicit recommendations concerning specific courses and their content, but we encourage innovative methods for delivering the graduate curriculum. Possibilities include using a more integrated approach to teaching the core subjects, for example, by combining several of the core subjects in one course. Departments might experiment with offering short courses in certain subjects where students may benefit from an introduction but not wish to take an in-depth course.

### Footnotes

1. *Policy Implications: International Graduate Students and Postdoctoral Scholars in the United States*, <http://www.nap.edu/catalog/11289.html#toc> OpenDocument (National Academies Press, May 10, 2005).
2. S. Nagel, "Physics in Crisis," *Phys. Today* 55, 55 (Sept. 2002).
3. "Core and Breadth in Physics Doctoral Education," Report of the AIP Statistical Research Center, <http://www.aip.org/statistics/trends/reports/Doceducation.pdf>
4. I.F. Rockman, *Integrating Information Literacy into the Higher Education Curriculum* (Jossey-Bass, San Francisco, 2004).
5. K. Kirby and F.A. Houle, "Ethics and the Welfare of the Physics Profession," *Phys. Today* 57, 42–49 (Nov. 2004).
6. See <http://www.aip.org/fyi/2001/099.html>; July 30, 2001.