DEPARTMENT OF PHYSICS AND ASTRONOMY

Long-Range Planning Document

November, 2005, revised January, 2007

Executive Summary

The Tufts Department of Physics and Astronomy is at a critical point. We have distinguished and exciting programs in research and in undergraduate and graduate education. Our faculty have been, and continue to be, engaged with the most significant questions of modern physics. Unfortunately, gradual shrinkage has left us barely able to sustain these efforts. Several fundamental courses are now offered only in alternate years, advanced courses are offered infrequently, and there is almost no room for special topics, experimental courses, or courses for non-scientists. If our faculty size decreases further it is doubtful whether our graduate program – and thus our research effort – could continue. Moreover, the age of our faculty makes it probable that about half the department will retire within the next ten years. Without an *immediate and sustained* commitment to reinvest in the department, the proud tradition of first rate physics at Tufts cannot be maintained.

This document presents a ten-year plan to enable the department to continue to serve Tufts University with distinction. Key points include:

- Restore the tenure-track faculty from its present size of 16 (17)[1] to its previous size of 19, and the graduate program from about 30 students to 40.

- Ensure that the elementary particle group continues at full strength in order to have a major impact in its recent initiatives in collider and neutrino oscillation experiments.

- Strengthen our programs in both astronomy and cosmology by including observational astronomers, theoretical astrophysicists, and particle physicists with our cosmological theorists in a broadened Institute of Cosmology.

- Create a new center of excellence in condensed matter physics, focusing on nanoscopic physics with bridges to biophysics.

- Reunite the department in a single building with adequate laboratory, office, teaching and meeting spaces.

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[1] Numbers in parentheses show the value assuming the current search (AY '06-'07) for a tenure-track assistant professor in astronomy is successful, in the absence of any retirements or other changes.

Introduction

The achievements of physics and astronomy constitute one of humanity's intellectual triumphs. We can describe and predict the behavior of matter and energy on scales that range from far smaller than an atom to far larger than a galaxy. We have extended our senses to observe and measure the structure of subnuclear particles and of the Universe beyond our galaxy. The ripples from these discoveries have washed over modern culture, forever changing humanity's conception of the way the Universe works and our place in it. No wonder *Time* magazine chose a physicist as the "Person of the [20th] Century". As we enter the 21st Century, great mysteries remain, including[2]:

- The birth, history and future of the Universe;
- Whether the four known fundamental forces are manifestations of a single unified interaction;
- The origin of mass;
- Whether there are undiscovered principles of nature, such as new symmetries, new physical laws, or extra dimensions of space;
- The nature and properties of the "dark matter" and "dark energy" that apparently comprise more than 90% of the Universe, and about which we know almost nothing;
- How to understand and predict the collective behavior of systems comprising many strongly interacting objects;
- The properties of systems intermediate in size between molecules and bulk materials, or that exhibit one- or two-dimensional behavior.

Tufts physicists and astronomers are actively engaged in the quest to solve these puzzles, and there is plenty of exciting work for future generations.

The practical impact of physics has been equally impressive. From the microscope to the laser, from the electric motor to the integrated circuit, from the radio to the global positioning system, our world teems with technology derived from the fundamental research of physicists. Nor has the flow of ideas slackened – hard disk drives now universally use magnetoresistive sensors based on physics discoveries made only in the last twenty years. Quantum computing has moved from the imagination to the laboratory, and practical implementation is now a distinct possibility.

Physics is the foundation of the other physical sciences and the life sciences. While the explosive progress in medicine and the life sciences over the last fifty years has attracted the attention of college students, Congressmen and industrialists, these extraordinary accomplishments owe a great but often overlooked debt to earlier discoveries in the physical sciences, such as x-rays, crystallography (which led to the deciphering of DNA's

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[2] Some of these fundamental questions come from *Quantum Universe: The Revolution in 21st Century Particle Physics*, DOE/NSF High Energy Physics Advisory Panel Quantum Universe Committee (2004).

structure), lasers, and magnetic resonance. Tufts' sole Nobel laureate, Alan Cormack, who received the Prize for Physiology and Medicine in 1979, was an experimental physicist whose primary research was on elementary particles. Future breakthroughs in biology may rely on the atomic-scale imaging capability of scanning probe microscopes, the data-sorting algorithms of experimental particle physics, or the image processing techniques of astronomy.

For students in all scientific fields, physics provides an indispensable conceptual foundation and rigorous training in quantitative reasoning. The National Research Council, in its recent report *Bio 2010: Transforming Undergraduate Education for Future Research Biologists* (National Academies Press, Washington 2003), emphasized the dependence of progress in the life sciences on a solid physical science foundation. The expert panel noted that "many of today's top biomedical researchers came to their work after undergraduate or graduate education in … physics and/or chemistry" and that "the connections between the biological sciences and the physical sciences, mathematics and computer science are rapidly becoming deeper and more extensive." Our department contributes to these linkages not only through standard instruction of life-sciences students in Physics 1 and 2, but also with biophysics research and specialized biophysics courses.

Physics also makes important contributions to other aspects of human activity, including public and environmental policy. Some of these contributions are reflected in such classes as Prof. Gunther's "Physics of Music and Color", Prof. Goldstein's "The Nuclear Age," and Prof. Tobin's courses on the physics of sports and on energy policy.

In view of the discipline's intellectual richness, technological contributions, and foundational relationship to other fields, it is no surprise that a strong physics-astronomy department is at the core of virtually every prominent school of liberal arts and every research university. Tufts has been no exception. To choose only a few examples:

- Since the creation of the FRAC Distinguished Scholarship Awards, a member of the physics-astronomy department has won every time the award was given in the Natural Sciences (Profs. Vilenkin, Schneps, Mann).
- Five of our faculty (almost one third) have been named Fellows of the American Physical Society. Our faculty have received distinguished fellowships, chaired major conferences and been spokespersons for large international collaborations.
- The Tufts Institute of Cosmology is world-renowned, and Institute faculty are regularly cited in popular articles and books on modern cosmology.
- Members of the particle physics group played essential roles in three major discoveries: the measurement of the mass of the top quark (1995), the demonstration of neutrino oscillations (1989-2002) and the direct detection of the tau neutrino (2000). The group has been continuously supported for nearly 50 years, initially by the Atomic Energy Commission and subsequently by the Department of Energy.
- By one measure of scholarly quality (citations/paper), the department was ranked in the top 20 in the country, ahead of all but a few of our comparator schools.

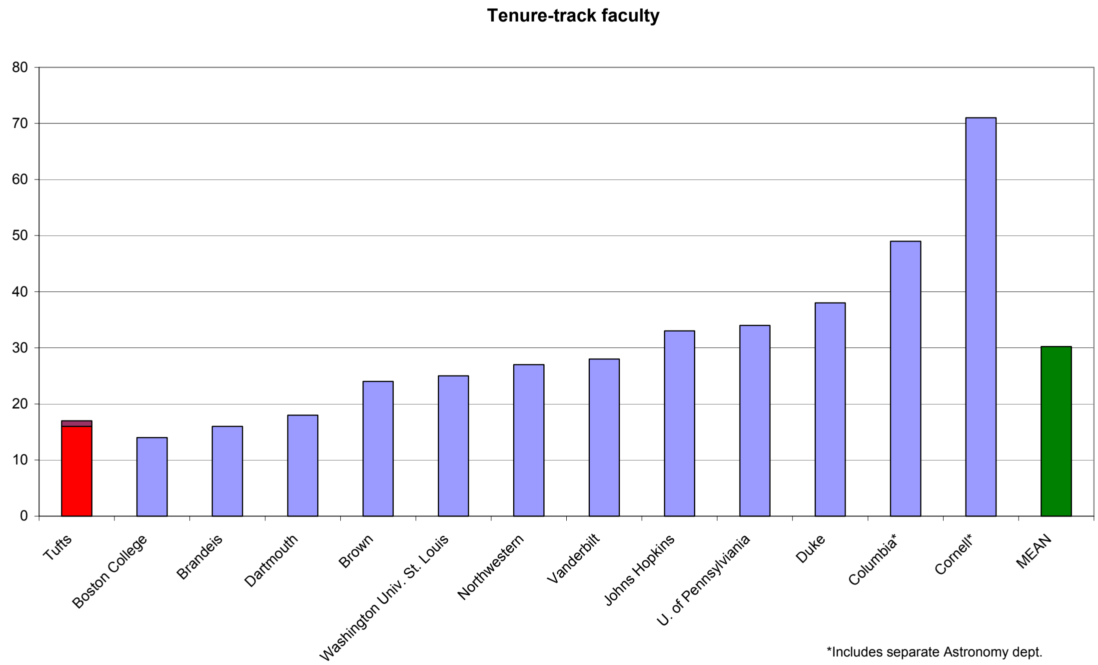

Figure 1. Number of tenure-track faculty in physics and astronomy at Tufts and peer institutions. The extra segment on top of the Tufts bar shows the change if the current astronomy search is successful.

- Over the past five years the department has received an average of $1.4 million per year in external funding, including grants from the NSF, DOE, NASA, and private foundations.
- Tufts physics PhD's are on the faculty of major universities around the world, hold responsible positions in industrial research, and have founded successful companies.
- Admission to our graduate program is highly competitive. In recent years we have rejected more than 85% of the 80-100 applicants each year, and more than half of those offered admission have chosen to attend.
- Our undergraduate majors frequently coauthor papers; regularly receive the Benjamin Brown, Victor Prather, and other competitive prizes and scholarships; and pursue graduate degrees at such universities as Harvard, Yale and MIT. Our graduate students also routinely receive GSAS awards for their research and teaching.

This record of success, however, is in jeopardy. A comparison with our peer institutions[3] shows that our department is now among the smallest, with only 16 (17) tenure-track faculty (See Fig. 1). (Even if the numbers are adjusted for school enrollment we are still below every comparator except Boston College.) It is clear why there are almost no departments with fewer faculty: At our present size we can offer only the minimal set of

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[3] The comparator schools are those designated by the Administration, plus Brandeis and Vanderbilt. Georgetown has been omitted because it does not have a graduate program in physics. Data are taken from the American Institute of Physics Guide to Graduate Programs in Physics (www.gradschoolshopper.com,) and the web sites of the individual departments and were current as of 2005.

courses necessary to sustain viable undergraduate and graduate curricula.[4] Several fundamental courses, including undergraduate electricity & magnetism and graduate mechanics, are now offered only in alternate years. Our undergraduate course in solid state physics has been offered only once in the past ten years. Advanced courses in condensed matter and particle physics are offered infrequently, and there is almost no room for special topics, experimental courses, or courses for non-scientists.

The danger can hardly be overstated. *With any further reduction in faculty size it is doubtful whether our graduate program could continue.* In fact, at least three additional faculty positions (*beyond* replacement of future retirements) are needed if we are to offer the excellent curriculum that Tufts students expect and deserve, to attract excellent faculty and graduate students, and to compete effectively with our peer institutions.

Figure 2 compares our fraction of tenure track faculty below the rank of Professor with the corresponding fraction at comparator institutions. Bluntly put, ours is a very old faculty. This situation has its advantages. Our faculty are well-established, productive and distinguished scientists who have "maintain[ed] an active research program throughout their career[s]"[5], and the department's prominence derives from their accomplishments and reputations. But with roughly half of the department approaching

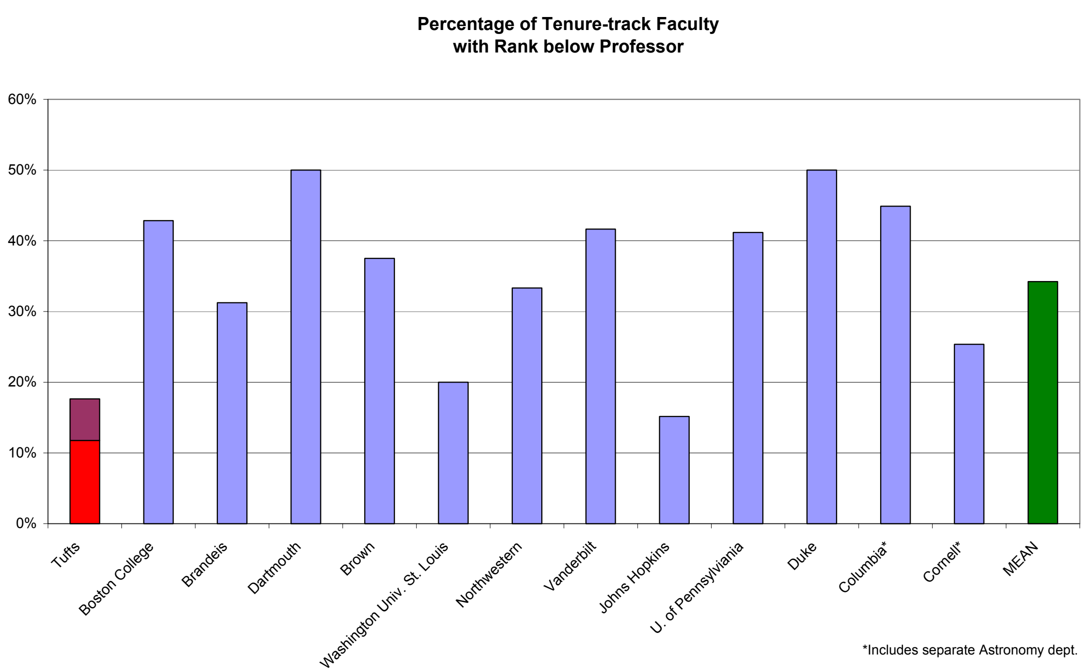

Figure 2. Fraction of tenure-track faculty in physics and astronomy below the rank of Professor, at Tufts and peer institutions. The extra segment on top of the Tufts bar shows the change if the current astronomy search is successful.

[4] The baseline teaching responsibility of physics-astronomy faculty is 2 courses per year, plus 2-4 recitation sections. This is equal to or greater than the typical teaching "load" at our comparator schools. Any increase would adversely affect our research efforts and put Tufts at a severe disadvantage in attracting first-rate faculty.

retirement, we are beginning to see diminutions in research activity, in opportunities for graduate students, and in external funding. Perhaps most importantly, we are starting to become deficient in the energy, excitement and new ideas in research and pedagogy that young faculty bring to a department.

Like other departments, we have also experienced a gradual increase in our reliance on part-time and non-tenure-track faculty. While these faculty are excellent and energetic researchers and teachers, their contingent status inevitably means that they cannot make the same contribution to the graduate program, to advising, and to service and governance as regular faculty[6]. The problem is particularly acute in the field of astronomy and astrophysics, where a single tenured faculty member is supplemented by four part-time or adjunct faculty. Our current search for a tenure-track observational astronomer, if successful, will begin to alleviate the problem, but will not eliminate it.

Given the department's demographics, it is all but certain that the next ten years will bring the retirement of about half the present faculty. This is therefore a particularly opportune time to reexamine our priorities, refocus our efforts, and consider how to configure Physics and Astronomy at Tufts for the challenges and opportunities of the next ten to twenty years. In the following sections we examine each of the major research areas of the department. After careful thought we do not see a need for drastic reconfiguration. Our research groups are productive and well-regarded, and promise to remain vibrant for the foreseeable future. A small department cannot be active in every area, but we see no glaring deficiencies. We do, however, propose to use this transition period to develop a new center of excellence in an exciting area of condensed matter/bio-physics, and to create new linkages between the Institute of Cosmology and our efforts in observational astrophysics and experimental and theoretical elementary particle physics.

Cosmology and Astronomy

Historically, both at Tufts and throughout the world, cosmology and astronomy have been largely separate fields, sharing an interest in the nature of the Universe but with little overlap in background, methods, or research topics. Astronomy has traditionally been heavily observational, using telescopes on the ground and in space to observe, measure and quantify the constituents of our Universe as it exists. Tufts astronomers have carried out world-class research on solar flares and other phenomena associated with the solar surface and atmosphere. At present, however, astronomical research is carried out almost entirely by non-tenure-track faculty. Although their work is of high scientific quality and of great appeal to students, not all of the associated funding comes to Tufts, and the impact on our graduate and undergraduate programs is limited. We are currently (AY '06-'07) interviewing for a new tenure-track assistant professor position in observational astronomy, which will begin a much-needed revival of the department's astronomical research program.

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[5] *Tradition and Innovation: A Strategic Plan for Scholarhsip in the School of Arts and Sciences of Tufts University,* August, 2005.

[6] The Committee on Strategic Planning for the School of Arts and Sciences has identified the increasing reliance on non-tenure-track faculty as an obstacle to the long-term excellence of the School. (*Tradition and Innovation: A Strategic Plan for Scholarhsip in the School of Arts and Sciences of Tufts University,* August, 2005.).

Cosmology, in contrast, has historically been a realm of pure theory, using the fundamental laws of gravity (general relativity) and quantum physics to analyze the possible origin, evolution and future of the Universe – and even of other, hypothetical universes. The Tufts Institute of Cosmology has contributed significantly to theoretical developments in inflation, cosmic strings, and quantum effects in the early universe. Cosmology faculty have also been involved in research in the broader arena of theoretical physics, including such topics as negative energy in quantum field theory and Casimir forces. Some of the research has resulted in predictions which, if verified, would constitute major discoveries; an example is the possible existence of cosmic strings in the Universe

In recent years the boundary between the two fields, never sharp, has become increasingly blurred. Astronomical measurements have shown that ordinary matter and energy constitute only a small fraction of the Universe, with the properties of the remaining 90% almost completely unknown. Extraordinarily detailed measurements of the primordial light left over from the Big Bang have placed stringent quantitative limits on the early history of the Universe. At the same time, observations of supernovae in distant galaxies have demonstrated, shockingly, that the expansion of the Universe is actually accelerating. Experimental data from high-energy physics, where accelerator energies now approach the conditions in the first moments after the Big Bang, are also having an impact on cosmological ideas. With these and many other developments, cosmology is becoming a science driven as much by observational data as by theoretical insights.

In the coming years we plan to strengthen research and teaching in both astronomy and cosmology by expanding the Tufts Institute of Cosmology to incorporate the increasingly vital contributions of observational astronomy and particle physics, while maintaining our highly regarded program in wide-ranging fundamental theoretical physics. The nucleus of the Institute will remain a group of three theoretical physicists. In such a rapidly developing field, theorists have the great advantage of being able to switch direction quickly in response to new ideas. It has been our experience that three is the minimum "critical mass" to maintain the level of intellectual ferment that has been vital to the exciting atmosphere of cosmology research at Tufts. We propose to add to this nucleus two tenure-track astrophysicists or astronomers who are closely engaged with newly emerging astronomical observations pertinent to cosmological questions. They will bring the latest in empirical findings, and the cross-fertilization between the theorists and observers can be expected to benefit the research and teaching of both. A search is currently underway for the first of these astronomers. Finally, because the insights and tools of elementary particle physics are becoming increasingly important in cosmology – neutrino astrophysics, for example – members of the elementary particle physics group whose work is of cosmological significance will also be affiliated with the Institute.

Elementary Particle Physics

Since 1957, the faculty of the Tufts elementary particle physics (EPP) group has pursued the study of elementary particles and the fundamental interactions in which these particles participate. Members of the group participated in the pioneering research that led to the development of the Standard Model of elementary particle interactions.

Faculty and students of the group played essential roles in the major discoveries of the last several decades. The Tufts collider physics group made important contributions to the detection and determination of the mass of the top quark, the heaviest of the fundamental constituents of matter. The Tufts neutrino group has been central to several of the most important discoveries in the physics of these ubiquitous, mysterious and elusive particles.

The Tufts EPP group has prepared the foundation for a first-rate program of intense physics exploration which it will pursue over the next five years. The group is deeply involved in both neutrino physics and research with high-energy colliding beams. They are founding members of the new MINOS neutrino oscillation experiment, in which the most intense neutrino beam ever built is directed from the Fermi National Accelerator Laboratory (FNAL) near Chicago, through the earth below Wisconsin, to an underground detector in an abandoned mine in northern Minnesota[7]. The detector will measure the properties of the arriving neutrinos and look for differences that may have developed during their travel from Chicago. Major elements of the detector were fabricated in the Science and Technology Center machine shop at Tufts. The collider group has for many years prepared the requisite foundation for experimentation that will be conducted in the next 15 years at the Large Hadron Collider (LHC). The LHC, scheduled to be completed in 2007, will generate collision energies that rival the earliest moments of the Big Bang.

The group's program includes initiatives that extend to the year 2020 and beyond. Tufts faculty are closely involved in planning and development for future generations of accelerator experiments, including the International Linear Collider, the top priority of the international high energy physics community for the next accelerator to be built after the LHC. Other initiatives at Tufts include design work for a high-resolution detector at FNAL to make precise measurements of neutrino interactions and for a million-ton water-Cerenkov detector to look for astrophysical sources of neutrinos.

Given that the fundamental questions about the nature of the Universe increasingly require data and ideas from particle physics as well as from astrophysics and theoretical cosmology, strengthening links between EPP and the expanded Institute of Cosmology described above should be one of the goals of future faculty hiring in elementary particle physics.

Condensed Matter Physics and Biophysics

Condensed matter physics (CMP) deals with the properties of matter in its solid and liquid states. It is the realm of semiconductors and superconductors, of magnets and membranes, of polymers and nanotubes, of quantum dots and artificial atoms. It is the field that gave us transistors, disk drives, optical fibers and laser pointers. Because it deals with the states of matter that largely comprise the world we live in, condensed matter physics has strong technological implications, and students with training in the field are in demand for positions in industrial research and development. It is also a highly interdisciplinary field with links to chemistry, materials science, electrical engineering and the life sciences. For all these reasons condensed matter physics is the

[7] This experiment was recently featured in the New York Times: K. Chang, *Tiny, Plentiful and Really Hard to Catch*, New York Times, April 26, 2005.

largest subfield of physics and astronomy, and represents a sizeable proportion of the faculty at all of our peer institutions.

Research in condensed matter physics is particularly important to an institution with a strong commitment to undergraduate education. Most of the experimental work is carried out on campus, offering excellent opportunities for undergraduate participation. In the past five years more than twenty Tufts undergraduates have participated in supervised research in the condensed matter physics group.

The current CMP faculty has diverse interests, with experimental work in magnetic materials, polymers, surface physics, and ultrafast optics, and with theoretical work on collective quantum phenomena. All of these efforts are productive and well regarded, as indicated by the usual measures of publications, grants, honors, and invited talks. Having the research spread over so many areas, however, prevents condensed matter physics at Tufts from developing the visibility enjoyed by the cosmology and elementary particle groups.

Over the next ten years, we propose to create a new center of excellence focused on nanoscopic physics with connections to biomedical science. "Nanoscopic" refers to structures with sizes on the order of one-billionth of a meter – too large to be thought of as molecules, yet small enough to have properties quite different from those of bulk materials. It is a scale at which tools, concepts and applications from physics, chemistry, materials science, biology and medicine converge to discover new phenomena and develop new technologies. Many biological processes involve structures in this range (such as proteins and cell membranes), and engineered nanoscopic objects hold promise as diagnostic and therapeutic tools. In recent years new methods for reproducibly producing and systematically characterizing such structures have made this one of the most exciting areas of condensed matter physics, as well as an area with great opportunities for collaboration across disciplinary boundaries. Optical and spectroscopic techniques from physics are being used, for example, to follow and manipulate the movement of individual protein molecules. Researchers at the Sackler School working to use viral proteins as building blocks for nanomechanical structures have consulted with members of our CMP group.

We envision hiring four new faculty (replacing Prof. Weaver, who passed away in 2006, as well as three anticipated retirements), equally divided between theoretical and experimental physics. The first hire should be made at a senior level to guide the further development of the center.

Teaching and Pedagogical Innovation and Outreach

Over 1100 students each year enroll in physics and astronomy courses, the vast majority at the introductory level, and nearly half in introductory astronomy, which is the most popular course in the University and is taken by roughly one quarter of all Tufts undergraduates. The department is committed to providing the best possible educational experience to the students in our introductory courses as well as to our majors and graduate students. We are also working to better meet the needs of other students, such as those interested in biophysics or in science education. Our activities in these areas include:

- Virtually all physics classes, including recitation sections, are taught by regular faculty. This is an important advantage for Tufts students over those at peer institutions, where recitations are usually taught by inexperienced graduate students;
- Active-learning techniques, including interactive lecture demonstrations and peer instruction activities with electronic response systems, have been implemented in large lecture classes;
- Innovative uses of computers have been introduced in Introductory Physics, Optics, and graduate courses;
- New courses have been created in Space Science Education and Biophysics;
- Physics and astronomy faculty participate in the Science Working Group of the NSF-funded Fulcrum Institute for training K-12 master teachers in science and the scientific method and in a new initiative to develop an elementary school curriculum that prepares students for the particulate model of matter;
- Faculty are actively involved in research on science education and in outreach to pre-service and in-service teachers.

At the same time, decreases in the number of faculty and teaching assistants and deteriorating infrastructure prevent us from offering our students the educational experience they deserve. At our present size we can barely offer the minimal set of essential courses. Some crucial classes are offered only in alternate years, and there is little room to develop new courses. Most of our astronomy courses are taught by non-tenure-track faculty, and even with a new tenure-track hire in astronomy the role of contingent faculty will still be substantial. Because of shortages of space and teaching assistants we can offer the students in our introductory classes only six laboratory experiments per semester. The physical state of the classrooms in Robinson Hall is deplorable, with antiquated or nonexistent facilities for incorporating modern technology.

In the coming years, we intend to extend our educational innovations by revising existing courses and developing new ones; redesigning the laboratory section of our introductory courses (including doubling the number of experiments), and working with the Education department and other departments in science, engineering and mathematics to improve offerings for pre-service and in-service teachers, at both the undergraduate and masters levels.

Conclusion

In order to maintain a world-class department in research and in undergraduate and graduate education, and to continue to grow and improve, the department will need institutional support, beginning immediately and sustained over the next ten years, in three main areas: faculty hiring, graduate student support, and facilities.

Faculty hiring

To achieve the goals laid out in this document, the department needs to increase the number of tenure-track faculty over the next ten years from the present level of 16 (17) to 19. This increase would return the department to its size in 1990, and would allow us again to offer a full range of fundamental courses at all levels: for graduate students, undergraduate majors, and nonmajors. Even with 19 faculty members we would still be below the average of our peer institutions both in absolute numbers and in the ratio of faculty to undergraduate population.

Because of the large number of anticipated retirements over the same period, meeting this goal will require *at least one new tenure-track faculty member per year*. Moreover, we will largely be replacing full professors with many years of service with new junior appointments. As a result the net cost, even including start-up funds, will be minimal.

Graduate student support

The number of graduate students enrolled in our department is smaller than at any of our peer institutions, as shown in Figure 3. Our ratio of graduate students to faculty is also at the bottom of the list. Limited resources for TA and RA support allow us to admit only four or five students per year, rejecting numerous highly qualified applicants. This small number results in undesirably small classes, especially at the advanced level, and impedes the development of a healthy graduate student culture. Over the next ten years we propose to increase the number of graduate students from the present level of about 30 to approximately 40.[8] We anticipate that half the increase will come from an increase in external grant funding as senior faculty without grant support are replaced by excellent junior researchers who can compete aggressively and effectively for outside grants. The remaining five positions could come from an increase in the number of teaching assistants. This increase would allow a doubling of the number of laboratory sections in the introductory physics courses, so that students would have laboratory every week, instead of every other week.

Facilities

The Department is currently divided between Robinson Hall (department offices, most instruction, offices for theorists and astronomers) and the Science and Technology Center (labs and offices for experimentalists). We propose that the reshaping of the department over the next ten years include reuniting it under a single roof, either at the STC or in a new building.

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[8] This is consistent with the proposal of the Committee on Strategic Planning for the School of Arts and Sciences to increase the size and resources of strong graduate programs. (*Tradition and Innovation: A Strategic Plan for Scholarhsip in the School of Arts and Sciences of Tufts University,* August, 2005.).

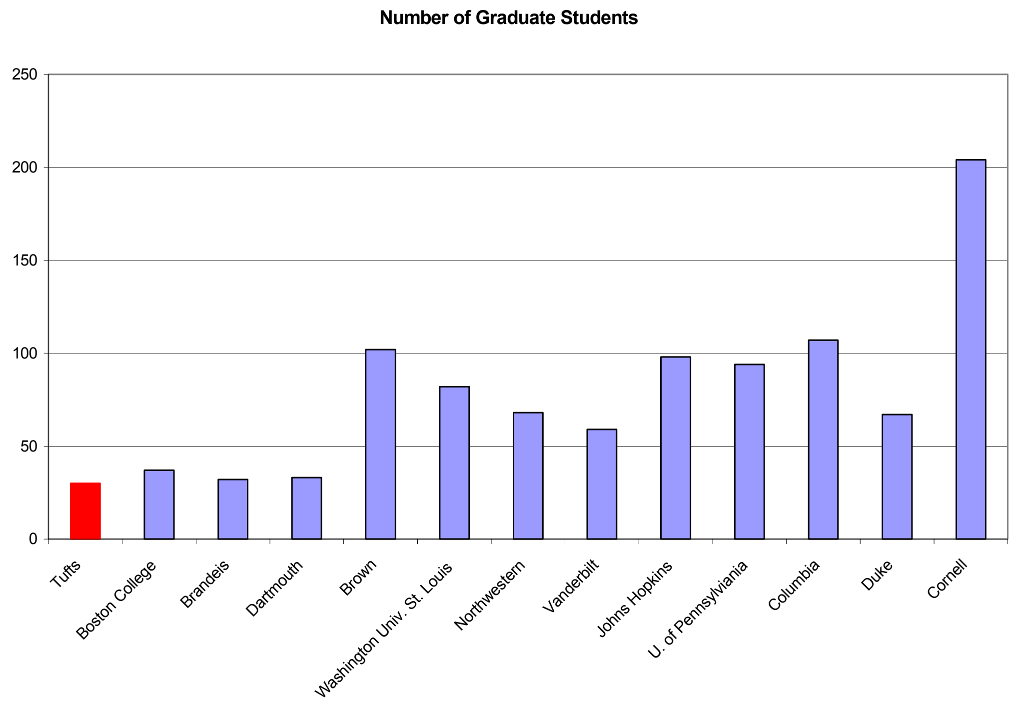

Figure 3. Number of graduate students in the Tufts physics-astronomy department and at comparator schools.

The glaring problems of Robinson Hall are so obvious and well-documented that there is no need to repeat them here. It is an embarrassingly substandard and outdated building. A complete internal renovation, creating modern classroom spaces and teaching laboratories, is long overdue and absolutely essential.

Even if Robinson Hall's physical deficiencies were corrected, however, the division of the department would still be detrimental. It is well established that productivity and creativity are enhanced by opportunities for informal interactions. The existing split, in contrast, greatly inhibits collaboration and conversation between experimentalists and theorists, at both the faculty and graduate student level. Attendance at seminars and colloquia is suppressed by the inconvenience. Perhaps most significant, first- and second-year graduate students, who because of their classes and teaching responsibilities spend most of their time at Robinson Hall, have little contact with advanced graduate students in experimental physics. Conversely, students who begin experimental work in their first two years find themselves isolated from their classmates, left out of study groups and social interactions. Uniting the department in a single building, with modern lab, office, seminar and computing facilities, would do much to improve the intellectual life of the department.

With an immediate and sustained commitment to excellence, the Tufts Department of Physics and Astronomy is well positioned to improve its already high stature, and to make an increasing contribution to research and education at Tufts. Absent that commitment, however, our ability to maintain first-rate undergraduate and graduate programs is very much in doubt.