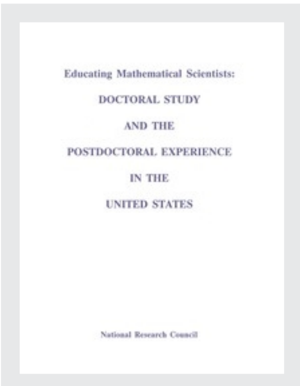

Educating Mathematical Scientists: Doctoral Study and the Postdoctoral Experience in the United States

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Educating Mathematical Scientists: DOCTORAL STUDY AND THE POSTDOCTORAL EXPERIENCE IN THE UNITED STATES

Committee on Doctoral and Postdoctoral Study in the United States
Board on Mathematical Sciences
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National Research Council

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PREFACE

Although the United States is considered a world leader in mathematical sciences research and in doctoral and postdoctoral education, concern is growing about whether the needs of the profession and of an increasingly technological society are being met. Many doctoral students are not prepared to meet undergraduate teaching needs, establish productive research careers, or apply what they have learned in business and industry. This inadequate preparation, continuing high attrition, and the declining interest of domestic students, the inadequate interest of women students, and the near-absent interest of students from underrepresented minorities in doctoral study are problems that transcend the current difficult job market.

One of the principal strengths of the American educational system is its diversity. No single paradigm for education at any level—doctoral/postdoctoral, undergraduate, secondary, or elementary—is imposed. Different programs can all be successful in accomplishing the same goals. This system encourages innovation and the development of local solutions that satisfy the needs of the profession and the country. Such local solutions can then spread, improving education everywhere.

A consequence of this system is that there are at present doctoral and postdoctoral programs that succeed in preparing their students for careers in teaching and industry as well as in academic research and succeed also in attracting large numbers of domestic students, including women and students from underrepresented minorities. But these programs have remained largely unnoticed by both the community and students. In an educational system that encourages innovation, the spread of successful innovative methods now seems to be stymied.

This observation was the starting point of this study. A study of the American doctoral and postdoctoral system of education in the mathematical sciences was proposed at a meeting of the Board on Mathematical Sciences in April 1990. With the support of the Alfred P. Sloan Foundation, the Committee on Doctoral and Postdoctoral Study in the United States was established in July 1990. Its charge was to determine what makes certain programs successful in producing large numbers of domestic PhDs with sufficient professional experience and versatility to meet the research, teaching, and industrial needs of our technology-based society and then to make this information available to the mathematical sciences community. The committee members were chosen to be broadly representative of the mathematical sciences.

Since the committee had neither the charge nor the resources to do a complete quantitative and qualitative study of all of the mathematical sciences doctoral/postdoctoral programs in the United States, it proceeded differently. In a two-day meeting in

September 1990, the committee reviewed data on these programs, clarified the definition of a successful program, and selected a diverse set of programs in 10 universities for two-day site visits, which were carried out in October-November 1990 and January-February 1991. These programs were in both small and large, and in both public and private, universities. They were also geographically diverse. They were all in the “top 100” and included four departments in the “top 20.” Achieving unanimity on the selections was no small task since the committee members had widely divergent opinions—some based on philosophical differences between the disciplines of the mathematical sciences—about what was important in doctoral and postdoctoral programs.

To minimize bias in the site visits, a uniform plan was prepared in advance for two days of observation and discussion by teams consisting of two (three for larger departments) members of the committee. Before the site visits began, a field test of this plan was conducted at a university not among the 10 universities chosen for the study, and, as a result, adjustments to the plan were made. Information to be collected before the site visit included the information packet sent to prospective graduate students, orientation material sent to new graduate students, orientation material sent to new faculty, completion rates for the different programs (with separate breakdowns for women and minorities), information on first-year courses, sample qualifying and candidacy examinations, a description of the duties and responsibilities of teaching assistants, a breakdown of funding sources for graduate students, and list for the previous five years of doctoral students, postdoctoral associates, and junior faculty appointments with information on their advisors, career tracks, and so forth.

The allocation of time during the visits was 50% for students, 25% for faculty, and 25% for administrators. At the beginning and end of the visit, the team held discussions with the chair(s) of the mathematical sciences department(s). The team also spoke separately with the following people and groups: director of the graduate programs, members of the graduate committee, graduate students (in small groups and in informal settings), women and underrepresented minority students (if enrolled in sufficient numbers), thesis advisors, junior faculty, postdoctoral associates, graduate secretary, supervisors of teaching assistants and of the teaching assistant orientation program, and the person(s) responsible for admissions and recruitment. The team visited the departmental and institutional libraries, the computing facilities for students, and students' office space and their space for socializing. It observed the opportunities for social interaction among students and between students and faculty.

Since the committee was not in any sense evaluating the programs at the universities it visited and because it wished to receive the full and open cooperation of the departments, no program identification is made in this report, nor are the site visit reports included. However, quotes from site visit reports are incorporated to illustrate the committee's findings. The statistical data presented during the site visits are not presented in this report, since an extensive statistical portrait of a restricted number of departments would not serve the committee's purpose.

After the site visits were completed, the committee met in March 1991 to analyze the results. At the end of two days of discussion, the committee was unanimous in concluding that the widely differing programs that had been visited by different teams did indeed have common characteristics that produced success. Moreover, the committee decided that one report was appropriate for all of the mathematical sciences.

The committee recognizes the limitations of this methodology. The result is a report that is often impressionistic in nature, but one that represents unanimous impressions of committee members with widely varying disciplinary and intellectual backgrounds. Within these limitations, the committee believes that it has a strong message to deliver in favor of adjusting the American doctoral and postdoctoral system of education in the mathematical sciences so that it responds better to the needs of the profession, students, and the society. The audience to which the report speaks is all U.S. doctoral and postdoctoral programs in the mathematical sciences, and, in particular, those programs that have limited human and financial resources. The report suggests that even with limited resources success can be achieved if, among other things, a program focuses its energies rather than trying to implement a “standard” or traditional program that covers too many areas of the mathematical sciences. It also notes that departments with the best faculty do not necessarily have the most successful doctoral and postdoctoral programs. A quality faculty is necessary for a good program, but of equal importance are students and researchers that can benefit from the program.

The committee was assisted in preparing this report by many people at the National Research Council and in the mathematical sciences community. The cooperation and assistance of the faculty, students, postdoctoral associates, and administrators at the 10 institutions visited by the committee were invaluable. While the committee wishes that these people and universities could be identified, this study was structured to keep their identities anonymous, since the intention was not to certify or advertise these programs but rather to use them as examples of what is possible.

The Board on Mathematical Sciences gratefully acknowledges support from the Alfred P. Sloan Foundation for this report.

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EXECUTIVE SUMMARY

Although the United States is considered a world leader in mathematical sciences research and in doctoral and postdoctoral education, concern is growing about whether the needs of the profession and of an increasingly technological society are being met. Many doctoral students are not prepared to meet undergraduate teaching needs, establish productive research careers, or apply what they have learned in business and industry. This inadequate preparation, continuing high attrition, and the declining interest of domestic students, the inadequate interest of women students, and the near-absent interest of students from underrepresented minorities in doctoral study are problems that transcend the current difficult job market.

The charge to the Committee on Doctoral and Postdoctoral Study in the United States was to determine what makes certain programs successful in producing large numbers of domestic PhDs, including women and underrepresented minorities, with sufficient professional experience and versatility to meet the research, teaching, and industrial needs of our technology-based society. The committee based its findings on site visits to a diverse set of programs in 10 universities carried out in late 1990 and early 1991. These programs were in both small and large, and in both public and private, universities. They were also geographically diverse. They were all in the "top 100" and included four departments in the "top 20."

The audience to which the report speaks is all U.S. doctoral and postdoctoral programs in the mathematical sciences, and, in particular, those programs that have limited human and financial resources. The report suggests that even with limited resources success can be achieved if, among other things, a program focuses its energies rather than trying to implement a "standard" or traditional program that covers too many areas of the mathematical sciences. It also notes that departments with the best faculty do not necessarily have the most successful doctoral and postdoctoral programs. A quality faculty is necessary for a good program, but of equal importance are students and researchers that can benefit from the program.

In this report, a "successful" program is understood to be one that accomplishes the following two objectives.

- All students, including the majority who will spend their careers in teaching, government laboratories, business, and industry rather than in academic research, should be well prepared by their doctoral and postdoctoral experience for their careers.

- Larger percentages of domestic students, and, in particular, women and underrepresented minorities, should be attracted to the study of and careers in the mathematical sciences.

In its site visits, the Committee on Doctoral and Postdoctoral Study in the United States looked for features that were present in successful programs as well as for elements that were detrimental to quality education. The committee noted that successful programs possessed, in addition to the *sine qua non* of a quality faculty, the following three characteristics:

1. A focused, realistic mission
2. A positive learning environment
3. Relevant professional development

A positive learning environment is an environment that provides the assistance, encouragement, nurturing, and feedback necessary to attract and retain students and to give them an education appropriate for their future careers.

The findings of the committee are as follows:

- There are several different models (missions) for programs, including

- the standard-model, which supports research in a broad range of areas, offers depth in each one, and has as its goal preparation for careers at research universities, and
- specialized models, such as the subdisciplinary model, the interdisciplinary model, the problem-based model, and the college-teachers model, which were seen to alleviate two large human resource problems, recruitment and placement, and to be conducive to clustering of faculty, postdoctoral associates, and students, a practice that helps create a positive learning environment and promote relevant professional development.

- Both standard and specialized programs can be successful. However, programs that do not have the human or financial resources to run a successful standard program should consider whether a specialized model might better fit their needs.
- New PhDs with a broad academic background and communication skills appropriate for their future careers are better able to find jobs.

- Active recruiting increases the pool of quality students. It does not just reapportion the pool. It also increases the number of women and underrepresented minorities. Students with strong mathematical backgrounds have a choice of studying mathematical sciences, physical sciences, engineering, law, medicine, and other areas. More of them can be attracted to the mathematical sciences.
- Clustering faculty, postdoctoral associates, and doctoral students together in research areas is a major factor in creating a positive learning environment.
- A positive learning environment is important to all doctoral students but is crucial for women and underrepresented minorities.
- All departments, including those characterized as elite and selective, need to provide a supportive learning environment.
- Doctoral students and postdoctoral fellows should receive broad academic preparation appropriate for their future careers in research universities, teaching universities, government laboratories, business, and industry.
- Doctoral students and postdoctoral fellows should learn teaching skills and other communication skills appropriate for their future careers.
- The number of postdoctoral fellowships in the mathematical sciences should be greatly increased so that such positions can be viewed as the logical next step after completion of the doctorate for the good student, not as a highly competitive prize for a select few. More postdoctoral fellowships should have applied, interdisciplinary, or pedagogical components.

Changing the American doctoral and postdoctoral system in the mathematical sciences so that it responds better to the needs of the profession, students, and the society is a task that requires the cooperative efforts of faculty, departments, professional societies, and federal agencies. The departments at research universities have a special responsibility to raise the level and increase the knowledge of talented but underprepared entering American doctoral students. Federal agencies should continue their programs and also increase their awareness of the impact of their programs on the doctoral and postdoctoral system. Professional societies should be involved in monitoring change in the universities, the agencies, and the community. But action, if it starts at all, will start from the faculty. The faculty should be aware that creating and maintaining a successful doctoral/postdoctoral program will require additional effort and time. The long-term benefits to the department, the students, and the society are clearly worth the effort.

1

INTRODUCTION

In the period since World War II, research in the mathematical sciences has flourished in the United States. Large numbers of graduate students and researchers from around the world have come to this country to study and to work in pure and applied mathematics, in well-established and new fields. The American system of doctoral and postdoctoral study and research in the mathematical sciences is considered by many to be an unqualified success, in contrast to the system of pre-college and undergraduate education.

The current scarcity of highly qualified domestic graduate students, often attributed to mediocre pre-college education and to related problems in undergraduate education, is seen by many as an unfortunate circumstance but not as a major problem. In the 1990–1991 academic year, only 43% (461 out of the adjusted total of 1061 reported in McClure, 1991, p. 1093) of the recipients of PhDs in the mathematical sciences from institutions in the United States were U.S. citizens (McClure, 1991), whereas during the 1960s, 82% of the recipients of such PhDs from U.S. institutions were U.S. citizens (NSF, 1988). Among the U.S. citizen recipients of PhDs in the 1990–1991 academic year, less than a quarter were women and less than a twentieth were from underrepresented minorities. American mathematical sciences departments, research laboratories, and industry are relying increasingly on students, faculty, and professional researchers from abroad because fewer and fewer American students are being attracted to study in the mathematical sciences and because the education that many of those students receive leaves them ill equipped to compete with their foreign counterparts.

Noting the scarcity of highly qualified domestic students and the current tight employment market, some maintain that the chief problem in the doctoral and postdoctoral system is overproduction of PhDs, a problem that should be solved by encouraging students to choose other disciplines and by reducing the number of doctoral students. Our over-reliance on academia for jobs for new PhDs is often not considered to be a problem, nor is the matching of doctoral education with the positions that graduates take considered to be a priority. Increasing production of PhDs since 1987, international events that have increased immigration of students and professional mathematicians to the United States, and a recession in the economy have indeed combined to produce what is now the most difficult employment market for PhD mathematicians since the 1970s. Further complicating the current picture are the indications that the demand for mathematical scientists will rise as the many mathematical scientists hired in the 1960s start to retire over the next decade (NRC, 1990b). The long-term growth in demand for mathematical scientists in academia, government, business, and industry and the expectation that the wave of immigration of mathematical talent to the United States will eventually taper off suggest that the country will be best served by a positive outlook that emphasizes attracting more domestic students into the mathematical sciences and giving those students proper foundations for their future careers.

A positive outlook that serves the interests of the profession and the country can be translated into actions intended to achieve the following two broad objectives:

- All students, including the majority who will spend their careers in teaching, government laboratories, business, and industry rather than in academic research, should be well prepared by their doctoral and postdoctoral experience for their careers.
- Larger percentages of domestic students, and, in particular, women and underrepresented minorities, should be attracted to the study of and careers in the mathematical sciences.

In this report, a "successful" program is understood to be one that accomplishes these two objectives. The needed renewal of the profession, as pointed out in the "David I" report (NRC, 1984), *A Challenge of Numbers* (NRC, 1990b), and the "David II" report (NRC, 1990c), requires larger percentages of domestic students. Although statistics invariably oversimplify the situation, the following two "completion rate" statistics concerning percentages of domestic students are useful in judging a program's success: (1) the percentage of students who entered the program five years earlier and who have received their doctorates, and (2) the percentage of students who completed their second year of graduate study four years earlier and who have received their doctorates. The first of these two types of completion rate is an appropriate measure of the success of highly selective programs, while the second is appropriate for less selective programs. The committee observed a number of programs for which both rates were well above 50 percent.

PURPOSE AND SCOPE OF THIS REPORT

The charge to the committee was to determine what makes certain doctoral and postdoctoral programs in the mathematical sciences successful in producing large numbers of domestic PhDs, including women and underrepresented minorities, with sufficient professional experience and versatility to meet the research, teaching, business, and industrial needs of our technology-based society. The mathematical sciences are considered to be pure mathematics, applied mathematics, statistics and probability, operations research, and scientific computing. Computer science, a separate discipline, is not included among the mathematical sciences.

The doctoral period considered in this report extends from the first year of graduate study through completion of the thesis, regardless of whether or not the student obtains a master's degree. The postdoctoral period is the first five years after receipt of the PhD. A postdoctoral associate, postdoctoral fellow, or, in common parlance, “postdoc,” is a recent PhD who has a fully funded position to do research. Since such a small number of new PhDs in the mathematical sciences enjoy postdoctoral fellowships, this report concerns not only postdoctoral fellows but also junior faculty working during the postdoctoral period.

The purpose of this report is to present and disseminate information about types of mathematical sciences doctoral and postdoctoral programs that succeed in attracting large numbers of domestic students, including women and underrepresented minorities, and succeed in giving their students academic and professional experience that is relevant to their future careers. There are U.S. programs that provide high-quality doctoral education to student bodies that are 80% American, have nearly 50% women, or have 30% underrepresented minorities. This report, based on the committee's insights gained in site visits to 10 universities, describes characteristics of these programs. What these programs do differently and what they and others consider to be their successes and their frustrations is information that this report seeks to make available to the community so as to encourage doctoral/postdoctoral program models that are relevant to the needs not only of academic research but also of teaching, government, business, and industry, and to increase the quality and number of domestic PhDs, especially women and underrepresented minorities.

This report follows on and is complementary to a number of studies by the National Research Council that examine the health of U.S. mathematical sciences research and education, including *Renewing U.S. Mathematics: Critical Resource for the Future* (NRC, 1984), *Everybody Counts* (NRC, 1989), *A Challenge of Numbers* (NRC, 1990b), *Moving Beyond Myths* (NRC, 1991b), *Renewing U.S. Mathematics: A Plan for the 1990s* (NRC, 1990c), and *Actions for Renewing U.S. Mathematical Sciences Departments* (NRC, 1990a). One includes the following pertinent summary.

> Graduate and postdoctoral training programs offered by mathematical sciences departments are key to the successful renewal of the profession and reform of mathematics education. Successful programs can attract individuals to a career in the mathematical sciences and can develop highly qualified teachers and researchers to stimulate, nurture, and train future generations. Is our present graduate and postdoctoral educational system in mathematics working well? The answer seems clearly to be that it could be much better. The community could attract more students to the study of the mathematical sciences, and more students entering graduate programs could succeed in obtaining doctorates. With nurturing and continued attention through good postdoctoral programs, more of these young people could develop into good mathematicians—some as teachers, some as researchers, and many as both. (NRC, 1990a, p. 13)

CONTENTS OF THIS REPORT

Chapter 2 gives a brief historical perspective of the mathematical sciences in America, with emphasis on doctoral and postdoctoral training.

Chapter 3 describes how some programs in the present system achieve success. Three characteristics of successful programs—a focused and realistic mission, a positive learning environment, and relevant professional development—are introduced in this chapter. The issue of having a high-quality faculty—a *sine qua non* of a successful program—is acknowledged but not discussed in detail in this report.

The heart of the report is Chapters 4–7, which treat the three characteristics of successful programs and human resource issues that must be taken into account. Chapter 4 discusses human resource issues; in particular, those related to domestic students, women, and underrepresented minorities are examined. A number of specialized missions for doctoral/postdoctoral programs are described in Chapter 5. Chapter 6 discusses a positive learning environment. Relevant professional development is described in Chapter 7.

Chapter 8 describes how faculty, departments, professional societies, and federal agencies can work together to create more successful programs.

A guide for self-evaluation by departments forms Appendix A. Appendix B includes advice to prospective doctoral students on how they can best choose a doctoral program. Appendix C is a brief discussion of master's degree programs in the mathematical sciences, a feature that may form a part of a well-rounded graduate program in the future as doctoral programs become more oriented toward wider job markets, including business and industry.

2

HISTORICAL PERSPECTIVE

The system of education evinced by mathematical sciences doctoral and postdoctoral programs in the United States has deep roots in the European system. The European emphasis on research, and, in particular, on fundamental research, has guided the development of the American system during the past half century. A brief overview of the history of the mathematical sciences in the United States suggests why this is the case.

The statistical and historical data presented in this chapter and on occasion in the rest of this report are taken from the annual AMS-MAA surveys in the *Notices of the American Mathematical Society* (1980–1991), *The Mathematical Sciences: A Report* (NRC, 1968), *A Century of Mathematics in America, Part I* (Duren, 1988), *Science and Engineering Doctorates: 1960–86* (NSF, 1988), and *A Challenge of Numbers* (NRC, 1990b).

THE EARLY YEARS

During the 19th century, mathematics consisted of pure mathematics, some mathematical physics (the applied mathematics of those days), and statistics. Statistics had a separate professional identity, fostered by the American Statistical Association, which was founded in 1839, and thus was the earliest domestic professional society in the mathematical sciences. However, statistics as an academic discipline was considered to be an integral part of mathematics. Europe was the center of mathematical research, and American mathematics relied mainly on European universities to train American doctoral students and on people trained abroad to staff American colleges and universities. A base for future development was built with the establishment in 1876 of Johns Hopkins University, the first American research university, the founding of the American Mathematical Society in 1888, and the development of research programs at the University of Chicago toward the turn of the century. Respected journals were established to disseminate and stimulate mathematical research, among them the *American Journal of Mathematics,* in 1878, the *Annals of Mathematics,* in 1884, and the *Transactions of the American Mathematical Society,* in 1900.

During the period 1910 through 1930, the American mathematical community was small but active. Strong programs grew at Harvard and Princeton Universities, joining that at the University of Chicago. Mathematicians played a role in World War I primarily by calculating trajectory and range tables. Concern for mathematics education was growing, as attested to by the founding of the Mathematical Association of America in 1915.

With the coming of modern manufacturing methods following World War I, statistics grew into a separate discipline of the mathematical sciences. Statistical quality control and sampling schemes, two of the major developments of the 1920s, had far-reaching consequences for industrial development prior to World War II. However, the training ground for the statistician was still the mathematics graduate programs.

In the late 1920s, the American mathematical community grew rapidly, aided by new support from foundations and a National Research Council fellowship program funded by the Rockefeller Foundation. The top research universities established research instructorships in mathematics, a precursor to the postdoctoral positions of a later era. These instructorships were nonrenewable term appointments for two to four years with slightly reduced teaching loads. They were funded by the universities and increased the opportunity for postdoctoral experience at research universities.

For mathematics as for other sectors of society, the Depression brought an increase in unemployment and a decrease in salaries. The job market remained difficult during this period, and many new job seekers found only temporary employment or positions at the pre-college level. In spite of the prevailing poor economic conditions, the 1930s were a period of growth for the mathematical sciences community: the number of doctorates awarded increased from 351 in 1920–1929 to 780 in 1930–1939. PhD production during the 1930s was fairly constant, with some 80 degrees awarded annually. About 15% of the degrees in mathematics came from three departments (at the University of Chicago, Harvard University, and Princeton University) that were rated as “distinguished” and a further 50% from a group of about 15 “strong” departments. Opportunities for postdoctoral education were increased with the establishment of the Institute for Advanced Study in 1932. The Institute for Mathematical Statistics, a professional society for mathematical statistics, was organized in 1935.

In the United States through the 1930s, teaching was emphasized, both in the way departments conducted their business and in the way graduate students were educated. The heavy teaching load of U.S. university and college faculty allowed little time for research. In much of Europe, however, the emphasis was on research, and faculty had a normal teaching load approximately half that of their American counterparts.

In the mid-to late 1930s, the political conditions in Nazi Germany induced a number of mathematicians at universities in German-controlled areas to emigrate to the United States. World-renowned mathematicians such as Richard Courant, Hermann Weyl, and Hans Rademacher were among the emigrés. The U.S. mathematical community was infused with mathematical talent that would have an effect for generations to come. The additional strain on the U.S. job market for mathematicians was noticeable but not severe. By the end of 1939, 51 mathematicians had left their posts at German-speaking universities and come to the United States. Some were hired directly by the Institute for Advanced Study and a few universities, while others were placed in temporary positions. Although efforts were made to avoid placing refugees in regular positions and using university funds for their support, some domestic faculty members still reacted negatively at a time when funds were limited, teaching loads were increasing, and native-born PhDs were without jobs.

THE ERA OF GROWTH

World War II provided new opportunities for mathematicians, including the newly immigrated mathematicians. World War II brought technology to weaponry. However, very few mathematicians—American or foreign-born—had the applied skills needed for the tasks at hand. Mathematics was forced to broaden its perspective to meet war needs, and many pure mathematicians learned to do applied work. Statistics increased in importance with the growing demand for quality control, sequential analysis, and analytical/statistical methods for solving dynamical problems such as bombing patterns. The new disciplines of operations research and computer science were born in the war effort.

By the end of World War II, the number of mathematicians who had come to the United States from countries affected by the war totaled only 120 to 150. These immigrant mathematicians and World War II profoundly changed the culture of the American mathematical community. The immigrant mathematicians added to the research and scholarship in the United States and became a driving force in changing the emphasis at many institutions from teaching to research. The war made new areas of research important and brought new sources of support, greatly strengthening the ties between the government and the mathematical sciences. Government support continued after the war through the Office of Naval Research (ONR), founded in 1947, and the National Science Foundation (NSF), founded in 1950. The new system of grants for summer research, graduate students, and conferences, as well as of peer review for the awarding of such grants, gradually changed the atmosphere in U.S. colleges and universities. Research became an integral part of the university structure, and institutions across the country sought to hire mathematicians capable of doing research and obtaining grants.

By 1951, the number of PhDs awarded annually was already over 200 per year. The horizons of the mathematical sciences were being widened. Applied mathematics, scientific computing, and operations research became recognized disciplines of the mathematical sciences. The Society for Industrial and Applied Mathematics was founded in 1951, the Operations Research Society of America in 1952.

By 1961, the number of PhDs awarded annually was well over 300 per year. The mathematics departments at Chicago, Harvard, and Princeton still had distinguished programs but now were joined by departments at Columbia University, the University of Michigan, Massachusetts Institute of Technology, Stanford University, the University of

California, Berkeley, and Yale University, which had moved up from the "strong" category. Other programs replenished the ranks of the strong departments, bringing the number of recognized programs to about 25. Strong departments of statistics also emerged during this period, among them the departments at the University of North California, Iowa State University, and the University of California, Berkeley.

The challenges facing the United States in the 1960s—to be first on the moon and to develop the technology base for economic and military security—strongly influenced both research and PhD production in the mathematical sciences. During this period, the number of doctorates conferred annually increased from 332 in the 1960–1961 academic year to 1070 in 1968–1969, and the number of doctoral programs went from around 200 to nearly 325. Throughout most of the 1960s, employment opportunities were unlimited for new PhDs. This situation was fueled by the growth in the number of research departments, increased enrollment in undergraduate mathematical sciences courses, and a new demand for mathematicians in government and industry. This was also a period of rapid growth for statistics. The number of doctoral statistics departments rose from 8 in 1950 to 17 in 1960 to 34 in 1970. The number of doctoral degrees awarded in statistics, including degrees awarded by mathematics, biology, and social science departments, increased from 110 in 1962 to 324 in 1972.

THE ERA OF CONTRACTION

The 1970s, however, was a time of great difficulty for many doctoral and postdoctoral programs in mathematics. During the 1970s, federal funding and employment opportunities decreased and the service role of mathematical sciences departments increased. Enrollment in undergraduate mathematical sciences courses continued to increase while the number of faculty positions remained level or decreased slightly. The mathematical sciences were increasingly viewed by many university and college administrators as a service discipline. Class sizes grew to accommodate increasing undergraduate enrollment, contributing to problems in collegiate mathematics. At many institutions, more of the undergraduate teaching load was shifted to graduate teaching assistants. This close identification of mathematics departments with teaching had serious implications as administrators looked for savings by promoting larger classes.

While undergraduate enrollment was increasing, graduate enrollment was decreasing. Graduate enrollment in the 155 PhD-granting mathematics departments declined by 17% from the fall of 1969 to the fall of 1974, while the decrease for the top 65 departments was 25%. The number of first-year graduate students decreased by nearly 50% at the top 65 departments. During the same period, federal support for graduate studies suffered a sharp decrease. Annual doctoral production reached a maximum of 1281 in the 1971–1972 academic year and then began to decline. The traditional mathematics programs reacted by looking inward and restricting access to the profession. Students were discouraged from pursuing doctoral studies in the mathematics. As a result PhD production in the mathematical sciences dropped further and took longer to recover than in any of the other sciences or in engineering. PhD production in the mathematical sciences continued to decline through the 1970s. By the 1979–1980 academic year, the number of new PhDs conferred had dropped to 745. However, the decline was not uniform over all areas of the mathematical sciences. The more applied areas of the mathematical sciences reacted by creating non-academic opportunities for their new PhDs to make up for the loss of academic positions. The number of doctorates awarded in pure areas decreased by 55%, while those in applied mathematics, statistics, and operations research remained roughly constant or increased slightly. This shift in emphasis from pure to applied areas was reflected in the strength of statistics during this period of decline for mathematics. The number of autonomous statistics departments continued to increase, reaching 65 by 1987. In this year, there was a total of 164 degree programs in statistics, including 47 degree programs in mathematics and mathematical sciences departments.

By the 1970s, computer science had emerged as a separate discipline with an identity distinct from that of the mathematical sciences. The growth of computer science and its establishment as a separate discipline drew students and resources from the mathematical sciences. Mathematics departments, which originally had had to teach computer science, were often left with a relative decrease in resources and a relative increase in service teaching when independent computer science departments were established.

During the late 1970s, concerns began to surface about not only the decrease in the number of new PhDs but also the decrease in the percentage of U.S. citizens among new PhDs and about underrepresentation of women and ethnic minorities. The percentage of mathematical sciences doctorates awarded to U.S. citizens decreased from 82% in the 1970–1971 academic year to 74% in the 1978–1979 academic year. Growing concerns for increasing the participation of underrepresented minorities and women in the mathematical sciences were made evident by the founding of the National Association of Mathematicians in 1969 and the founding of the Association for Women in Mathematics in 1971.

Instead of increasing the employment opportunities for mathematical sciences PhDs by making mathematicians more employable in nontraditional institutions, most of the community worked to restrict the number of PhDs to fit the small traditional marketplace. When stability in the employment market returned at the start of the 1980s, many mathematical scientists realized that severe problems had been created by this inward-looking attitude. Despite success in both research and advanced study, the mathematical sciences in the United States were now unable to attract sufficiently many domestic graduate students for renewal. In addition, a serious imbalance had developed in federal funding of the mathematical sciences as compared with other sciences.

One of the first reports to call attention to the imbalance in funding was the report *Renewing U.S. Mathematics: Critical Resource for the Future* (NRC, 1984), which was influential in bringing about a modest increase in federal support for the mathematical sciences. By 1987, however, there was still nothing close to a balance with other fields. In 1987, 75% and 56% of the R&D faculty in physics and chemistry, respectively, received federal support, whereas only 37% of the mathematical sciences R&D faculty received federal support. In that same year, 51% and 49% of the graduate students in physics and chemistry, respectively, received federal support, whereas only 18% of the mathematical sciences graduate students received federal support. A reassessment, *Renewing U.S. Mathematics: A Plan for the 1990s* (NRC, 1990c), summarized the effects of the 1984 report and argued strongly for the continued need for increasing federal funding.

THE RECENT PAST

In contrast to the preceding three decades of rapid change, the 1980s was a period of stability for the mathematical sciences. In spite of some competition with computer science for students, the number of PhDs awarded annually in the mathematical sciences was roughly constant, decreasing from 839 in the 1980–1981 academic year to a minimum of 726 in the 1984–1985 academic year and then increasing to 1061 in the 1990–1991 academic year. But the trend toward a higher percentage of non-U.S. citizens receiving degrees accelerated sharply. In 1980–1981, 68% of the doctorates granted by U.S. institutions in the mathematical sciences went to U.S. citizens, whereas in 1990–1991, only 43% of the doctorates awarded went to U.S. citizens. Increasing undergraduate enrollments, a booming economy, and retirements provided job opportunities for almost all new PhDs in the decade.

3

THE PRESENT SYSTEM AND SUCCESSFUL PROGRAMS

The recent technological explosion has continued to broaden the horizons of the mathematical sciences. But even though much of the new work in applied mathematics, statistics, operations research, and scientific computing has close ties with industry, the bulk of the mathematical sciences community is still employed in academia. Chapter 2 described the European influences that helped shape this system so oriented toward educating research mathematicians for employment in academic research. It is still the case that the doctoral curriculum at many institutions is restricted to classical core mathematics and that traditional educational methods are used. As a result, many researchers lack the broad knowledge needed to address real-world problems, many junior faculty members lack the direction to carry on their research and the experience to acquire funding to support their research, and the system of education is more or less self-contained, with graduates teaching what they have been taught in the same manner that they have been taught. Restricted career opportunities for mathematicians go hand in hand with a system oriented toward educating mathematicians for employment only in academic research.

At present, a large majority of the doctoral and postdoctoral programs in the United States are "standard-model" programs that educate research mathematicians for employment in academia and give too little attention to training for teaching. The following brief description of a research university provides insight into the increasing need for research universities to prepare mathematical scientists who can also teach and who can work effectively in government laboratories, business, and industry.

> A research university is a large, complex institution with a multiplicity of purposes. A large staff of researchers, postdoctoral fellows, and other professionals as well as faculty and students, both graduate and undergraduate, are involved in research, education, and service. The nation, the states, and local communities rely on research universities for most of the basic research that is done in the United States as well as for a large part of the applied research. Research universities educate a large proportion of the scholars, researchers, and teachers not only for schools, colleges, and universities but also for business and industry. With few exceptions, all doctoral degrees awarded in the United States are from research universities….
>
> Research and graduate education are often seen as the primary mission of a research university, especially in engineering and the sciences. This emphasis often influences other priorities, although … undergraduate teaching is a growing concern. States and the nation look increasingly to

> research universities for economic development and to maintain or regain economic competitiveness. Finally, society also looks to research universities for leadership in health care and social programs.
>
> Faced with this overwhelming set of institutional responsibilities, a department of mathematical sciences at a research university is pulled in many directions. It is called on to teach mathematics (often including statistics) at all levels to an increasing number of students; to maintain research excellence and help support such excellence in engineering and the sciences; to help support the renewal and invigoration of school mathematics; and to help recruit and attract American students to mathematics and areas depending on mathematics. (NRC, 1991b, p. 7)

Due to increasing production, to a large influx of researchers from the Soviet Union, China, Eastern Europe, and elsewhere, and to an economic downturn in the United States, the 1990s have brought a tight employment market with few permanent academic research positions for new PhDs. The increasing production of PhDs (adjusted totals of 884 in 1988–1989, 929 in 1989–1990, and 1061 in 1990–1991 reported in McClure, 1991, p. 1093), normally a sign of health in the field, is currently a mixed blessing because of the following two facts:

- Although many students are educated for the few jobs in academic research, only a few students are well educated for the many jobs in teaching, government laboratories, business, and industry.
- Although there are more new PhDs, there are still too few new domestic PhDs, in particular, women and underrepresented minorities.

Although the number of new U.S. citizen PhDs has risen recently—there were 411 in 1988–1989, 410 in 1989–1990, and 461 in 1990–1991—the percentage of U.S. citizens among all new PhDs has decreased, from 46% to 43% to 43% (for the same three years). The number of female U.S. citizen recipients of the PhD was 98 in 1988–1989, 89 in 1989–1990, and 112 in 1990–1991. These numbers represent 24%, 22%, and 24%, respectively, of the new domestic PhDs granted in those years. However, these modest figures have been achieved not so much because the number of women receiving PhDs has increased dramatically but because the number of men has decreased. By way of comparison, among the 634 new U.S. citizen PhDs in 1977–1978, 545 were men and 89 (14%) were women, whereas among the 461 new U.S. citizen PhDs in 1990–1991, there were 349 men and 112 (24%) women. The numbers of underrepresented minorities among the new U.S. citizen PhDs continue to be small: in 1990–1991, 10 African-Americans, 6 Hispanics, and 2 Native Americans received a PhD in the mathematical sciences. Although some have questioned whether there are now too many new PhDs for the current employment market, it is clear that both the number and the percentage of new domestic PhDs, especially of women and underrepresented minorities, is far too small.

If the profession in general misses the opportunity to work toward a broader vision of U.S. graduate education in the mathematical sciences and also reacts to the current tight employment situation by again looking inward, the result may be a further decrease in both the number and the quality of domestic students in graduate programs. Fortunately, however, some U.S. programs have already moved beyond accepting a limited employment market and limited human resources as facts of life, and seek instead to educate students and postdoctoral associates in ways that make them employable in a wider range of jobs and to attract larger numbers of domestic students, including women and underrepresented minorities, to studies in the mathematical sciences. This report provides information to departments about which methods are already producing success and which are detrimental to success in these two areas.

CHARACTERISTICS OF SUCCESSFUL PROGRAMS

In its site visits to 10 doctoral/postdoctoral programs, the Committee on Doctoral and Postdoctoral Study in the United States looked for features that were present in successful programs as well as for elements that were detrimental to quality education. The committee noted that successful programs possessed, in addition to the *sine qua non* of a quality faculty, the following three characteristics:

1. A focused, realistic mission
2. A positive learning environment
3. Relevant professional development

The committee also observed during the site visits that there were in some cases significant differences between groups in the same department. One group might be successful in attracting and educating doctoral students or in training postdoctoral fellows and advancing their careers, whereas another would be struggling at both. The degree of success of each part of the program correlated well with the presence of the three characteristics mentioned above.

In Chapters 5, 6, and 7, these three characteristics are discussed in detail. First, however, human resource issues are discussed in Chapter 4.

4

HUMAN RESOURCE ISSUES

Undergraduate mathematics programs have traditionally produced excellent students. The number of undergraduate mathematics majors increased during the 1980s, but most of these students either ended their education with a bachelor's degree or chose graduate or professional study in other fields. Fewer students continue their studies in the mathematical sciences than in other sciences and engineering. From 1977 to 1986, the attainment rate (the percentage of bachelor's degree holders who receive PhDs) in mathematics was 4%, somewhat lower than the 5% rate in all natural sciences and engineering (NRC, 1990b, p. 48). Mathematical sciences B.S. graduates who earn doctorates often earn them in other sciences or in engineering.

The fact that many excellent students who complete bachelor's degrees in the mathematical sciences either do not continue their studies or go on to graduate studies in other fields is an indication that the pool of candidates for doctoral study in the mathematical sciences is not being fully tapped. The programs visited by the committee show that the pool of highly qualified domestic doctoral students can be increased by active recruiting and that the completion rate (percentage of students who complete the PhD) can also be increased. In this chapter, human resource issues—ranging from recruitment of first-year graduate students to placement during the postdoctoral period—are discussed. Both the successful and the detrimental features described here are based on observations made in the committee's site visits.

RECRUITMENT

The conventional approach to recruiting consists of sending out announcements and posters to other institutions, listing teaching assistantships and fellowships in professional society publications and elsewhere, responding to inquiries, reading applications, and selecting students with the best credentials. Since students commonly apply to a department based on its research reputation alone, and not on other characteristics of the doctoral program, this type of passive recruiting works for programs with the best reputations. However, passive recruiting attracts only those undergraduates who are already committed to graduate study in mathematics. Departments typically compete for applicants only from the pool of students who have already decided to attend graduate school in the mathematical sciences, a group that includes too few domestic students, even fewer women, and almost no students from minorities. The committee believes that the custom of enrolling only those students who decide on their own to attend graduate school and to complete a doctoral program sustains the imbalance in the nationality, race, and gender distributions among doctoral students and postdoctoral associates in the mathematical sciences.

Active recruiting can result in the enrollment of a high percentage of domestic graduate students and a large number of women and minorities.

> The program is able to attract so many American students because it recruits so actively. It recruits primarily from small liberal arts colleges and has over the years developed contacts with faculty members in these schools. It works at maintaining friendly relationships with these contacts, accepting students who are highly recommended, in order to keep the pipeline open. The process is as follows. In each November and December the entire faculty sends letters to friends at four-year colleges and state universities requesting names of qualified students. Application materials are sent to all those recommended and are followed up with telephone calls.
>
> Committee Site Visit Report
>
> The department has a history of successfully recruiting female students. Word of mouth, the department's general reputation, and post-application visits and telephone calls by the graduate chairman and other faculty help attract female students.
>
> Committee Site Visit Report

Networks with departments at the colleges and smaller universities in a region can be set up. The faculty of a doctoral program and the faculty of the other departments may trade visits to get acquainted with both programs and people.

> Recruiting is very active and comparatively aggressive. The vice-chairman for graduate students routinely makes three or four telephone calls to prospective students, and students often expressed appreciation for this aggressiveness. Their graduates exist throughout the educational system and they send their students back. Alumni contact is important.
>
> Committee Site Visit Report

Faculty members should be encouraged (by travel support and other means) to speak with juniors and seniors at the colleges and universities they visit professionally. Former doctoral students and other faculty contacts in undergraduate programs, in particular, programs in local teaching departments, can be used effectively.

> The recruiting process has involved sending faculty members out to initiate contacts with many of the liberal arts colleges of the region. In many cases, pipelines with some of the best mathematics programs are now established, and [former] graduate students are asked to return to their undergraduate

> schools to talk about the program. They often get partial support from the department for this. Promising applicants are often invited for one-day interviews/visits at the department's expense and are given the red-carpet treatment.
>
> Committee Site Visit Report

Prospective students can be invited to visit a department. Getting to know the faculty can cause students not already committed to graduate study to decide to choose it.

> The 20 to 30 top applicants for the PhD are brought to a workshop in early March. They arrive Saturday and spend Sunday hiking with faculty. On Monday and Tuesday, faculty give lectures presenting their research interests, and the nature of the graduate program is explained. By all accounts, this is an extraordinarily effective recruiting mechanism. It builds enthusiasm for the program and an esprit de corps among prospective students. The workshop is followed up by telephone calls. One student told us that a major factor influencing his decision to come was that the department's persistence in trying to reach him convinced him that he was really wanted.
>
> Committee Site Visit Report

Information that shows the success of the new PhDs produced by the department in obtaining good jobs can be very convincing to prospective students.

> During the winter, the chair and associate chair visit approximately 10 schools each to give talks and to speak with interested junior and senior students. A typical talk is about one hour, with the first half hour devoted to some mathematical topic accessible to undergraduates. The second half hour is split roughly between a general discussion of graduate education in mathematics and discussion of the special features of their program. Because they put such a high priority on tracking their students' first employment following graduation, they can share this information with students during and after the talks as well as in application materials.
>
> Committee Site Visit Report

Paradoxically, one source of doctoral students that seems to be underutilized is the pool of mathematical sciences undergraduates at the research universities themselves. While some of the best undergraduates at a particular research university are encouraged to pursue doctoral study, there is usually no systematic recruiting of the remaining mathematical sciences undergraduates at a research university by anyone, the university's own mathematical sciences doctoral program or that of any other university.

In spite of the current tight employment market, recruiting is important. The students recruited today will quite possibly enter a much more favorable job market when they graduate. Even if the overall number of doctoral students is reduced to fit a smaller market that is not as favorable as some predictions indicate, it is important to increase the number and percentage of domestic doctoral students by active recruitment.

ADMISSION

Successful programs generally adopt one of two strategies for admission. The first strategy is a highly selective policy that results in a student body with high ability, preparation, and motivation. The doctoral programs with the best reputations for research can be highly selective about the students they admit, since prospective students often equate its reputation for research with the overall quality of a doctoral program. For other departments, a selective policy can be pursued as long as the department actively recruits students and ensures that the pool of candidates is sufficiently large. A second strategy is a less selective, more open admission policy that provides opportunities for talented but less well prepared students to study in the mathematical sciences. In successful programs, this strategy is coupled to a commitment to provide the additional support and opportunities for appropriate course work necessary to give the students a chance to succeed.

Many programs, under the pressure of decreasing interest in graduate study in the mathematical sciences among domestic students and the need for teaching assistants to staff undergraduate courses, have a somewhat open admission policy. Underprepared students admitted in this manner are often not provided with opportunities for appropriate course work, and many of them discontinue their studies. If recruiting is active, the pool is likely to be large enough so that students need not be admitted for the purpose of filling positions as teaching assistants.

DOMESTIC STUDENTS

There has been a sharp decline in the number of American doctoral students in the mathematical sciences during the past two decades. In the 1970–1971 academic year, 1009 (82%) of the 1238 mathematical sciences PhDs granted in the United States went to U.S. citizens, whereas in the 1990–1991 academic year, only 461 (43%) of the 1061 new PhDs went to U.S. citizens.

The drop-out rate from the mathematics career pipeline (beginning at the undergraduate level and terminating at the doctoral level) averages 50% per year, which is markedly higher than the corresponding rates in the other sciences and in engineering. Many American undergraduates take the minimal number of mathematics courses necessary to complete their major, which is a large factor in fewer of them going on to graduate school: limited exposure to mathematics in undergraduate school leaves American students at a disadvantage in the competition with foreign students for admission and support as well as in their studies. Yet it is clear that many American students are talented and would make excellent graduate students with additional study and seasoning.

> … the Department believes that American students are often not very well prepared for graduate study in comparison to foreign students and that they need "minority nurturing." Students who come from small schools are accustomed to individual attention and therefore are given special attention during the first semester, when nearly all of the drop outs in the program occur. Classes are small and faculty doors are open.
>
> Committee Site Visit Report

Although the major portion of funding for educating mathematicians and statisticians comes from universities, federal programs also affect the community, often beyond the intended primary purpose. Many federal research programs in the mathematical sciences have had the effect of attracting students to the mathematical sciences but have also had an unintended effect of decreasing the attention paid to teaching, because more time spent competing for grants often means that less time is spent on teaching. While this seems to be less of a problem in sciences with undergraduate laboratories, it may be a contributing cause for the decline in the number of domestic graduate students in the mathematical sciences.

One of the earliest federal programs for domestic doctoral students was the Predoctoral Fellowship Program at the NSF. The mathematical sciences participate, as do all the disciplines supported by the NSF. The Predoctoral Fellowship Program attracts some of the best undergraduates, and, for this reason, it is unlikely that the program increases the pool of students interested in graduate study. Any mathematics student who is competitive for this program would also be assured of full support in an elite program. Nevertheless, this program continues to demonstrate the importance attached to doctoral education by the federal agencies.

The recently introduced Graduate Assistance in Areas of National Need (GAANN) Program at the Department of Education is structured differently. Graduate programs compete for a block of fellowships that a department can award to domestic students who enroll in its program. Having the fellowships to award has caused many departments to start actively recruiting graduate students, with special emphasis on American undergraduates. Although the short-term effect of the GAANN Program might be to shift American students to graduate programs with GAANN support, the long-term effect should be to increase the domestic pool by attracting some of the bright mathematics majors who would otherwise enroll in graduate and professional programs in other sciences, engineering, medicine, or even law.

The committee visited a number of programs in which the proportion of domestic students was between 50% and 75%. All of them were actively recruited.

> The large number of enthusiastic domestic students was one of the striking aspects of the program. We believe that the factors bringing this about include (1) the esprit de corps initially established during the recruiting workshop and then strengthened during the first year, (2) active faculty interest and accessibility, (3) a supportive atmosphere, (4) a system of qualifying exams that is perceived as well defined, reasonable, and fair, and (5) the attraction of interdisciplinary studies.
>
> Committee Site Visit Report

WOMEN AND UNDERREPRESENTED MINORITIES

Although female U.S. citizens constitute almost one-half of undergraduate majors in the mathematical sciences, they still accounted for only 24% (112 out of 461) of the U.S. citizen recipients of PhDs in the 1990–1991 academic year. The PhD completion rate for underrepresented minorities is lower than that for women. Of the 461 U.S. citizen recipients of PhDs in 1990–1991, only 10 were African-American, 6 were Hispanic, and 2 were Native American. The job market projections for the next decade point to a need for greater representation by women and underrepresented minorities in order to meet U.S. requirements for people with expertise in the mathematical sciences (NRC, 1990b).

> The losses of mathematical talent are not evenly distributed among racial and ethnic groups or the sexes. At each critical juncture in the pipeline more women and minority students drop out than do white males. (NRC, 1990b, p. 35)

Few research universities have more than one or two women in their mathematics departments, and even fewer have minority faculty. Thus women and minority role models are scarce in the mathematical sciences. In several of the committee's site visits, graduate students, both male and female, pointed out the paucity of women on the faculty. But in some other departments, committee members' questions on this topic were met with indifference.

The concerns of women interviewed by the committee were similar to but more pronounced than those of domestic students in general.

> Women students report neither more nor less support from mentors than they believe is received by male students. However, more female than male students appear to drop out from frustration or other personal reasons after they have completed the first exam.
>
> Committee Site Visit Report

> My impression is that the PhD completion rate is low. A woman student attributed this mainly to lack of encouragement. She was interested to learn that a group of [domestic] male students had expressed the same concerns about lack of encouragement.
>
> Committee Site Visit Report

The committee observed in its site visits that departments that provide a positive atmosphere and expect women and underrepresented minorities to succeed often find that they do indeed succeed.

> There is an unusual amount of individual attention given [in the program], and the students appreciate it. Most of them came because of the interest expressed in them, an interest that does not diminish once they arrive. For women and minorities, the completion rate is 100% and [the rate] appears to be unusually high for all students. Every student seems to know where she/he is going at all times. Faculty are perceived to be extremely approachable, and we heard the term “open door policy” used frequently by students to describe the department.
>
> Committee Site Visit Report

The same type of active recruiting that is effective for domestic students in general is effective for women and underrepresented minorities. Nevertheless, some universities choose to “jump start” a program.

> There is a substantial and fairly effective program to help draw more women and minority students. This program is accorded 10% of the admission and support resources. After the admissions committee drafts its list of offers, 10% of the (total) offers are selected from the remaining applicants, with special attention given to women, minorities, students from weaker institutions, and so on. A similar procedure is followed in the award of support.
>
> Committee Site Visit Report

At present several fellowship programs are directed toward women and underrepresented minority students. The NSF Minority Predoctoral Fellowship Program awards a small stipend to the undergraduate school from which the fellow has graduated. The Department of Education's Ronald E. McNair Post-Baccalaureate Achievement Program provides support to juniors and seniors from first-generation college families and encourages them to pursue graduate study.

FOREIGN STUDENTS

Foreign students, now a majority in many doctoral programs, often have a higher level of mathematical experience than do American students. In many foreign countries, undergraduate students take many more mathematics courses than do most American undergraduates. In addition, some foreign students have completed a master's degree before coming to an American graduate program. The result is that, on entrance to a doctoral program, foreign students commonly have a one-to two-year advantage over American graduate students. Most domestic students and even many faculty members are not aware of this situation. When placed in the same introductory courses, foreign students thus often perform better than the American students. The committee believes that such a disparity can contribute to an increase in the drop-out rate among domestic students, especially among women and underrepresented minorities.

> There was some tension in the first two years between American and foreign students, the latter typically arriving with a more advanced level of training. Some of the American students confessed to being somewhat intimidated by this difference in the beginning.
>
> Committee Site Visit Report

Those foreign students who have already had first-year graduate courses should not be allowed to repeat these courses for reasons related to language and acculturation but should be placed in higher-level courses immediately.

Colleges and universities have of necessity had to rely increasingly on foreign nationals to teach undergraduate mathematics. The long-term ramifications and impact of this practice need careful study.

PLACEMENT

Every department should take an active role in the placement of new PhDs, an effort that currently is often viewed as the responsibility of the student and the thesis advisor alone. The networks used for recruiting students can be used for placement in academia. Faculty and alumni contacts can be used to facilitate placement in academia and industry. Relationships established in industry-related research and apprenticeship programs can be used to help place new PhDs in industry.

A large fraction of new PhDs go to faculty positions at institutions that view teaching as their primary mission. In 1990–1991, 80% of the new doctorates employed in the United States took positions in academia, and 50% of those took positions at institutions that did not offer a doctorate (McClure, 1991). Placement would be facilitated if students were prepared by their educational experience to become effective teachers. Graduates should be prepared by their programs of study to make the transition from highly active research programs to institutions with a smaller degree of research stimulation.

In addition to many tenure-track positions, non-tenure-track instructorships and assistant professorships are available at research universities. Temporary appointments with large teaching obligations are a growing phenomenon. It is not uncommon for new PhDs to hold two or more of these temporary positions before obtaining a tenure-track position. In such positions, time is spent mainly on teaching and seeking a job for the following year. Universities could treat temporary faculty as postdoctoral associates with teaching duties. Hiring in areas of strength and having senior faculty members act as research mentors would be a “win-win” strategy for both the department and the temporary faculty.

A new PhD with a broad applied background has opportunities in government, business, and industry and is less dependent on temporary positions in academia. In 1990–1991, 140 (20%) of the new doctorates taking jobs in the United States took non-academic positions in government, business, and industry (McClure, 1991). This figure represents a large increase over the 107 (16%) new doctorates in 1989–1990 who took jobs in government, business, and industry (McClure, 1991). However, most of the increase came from those holding degrees in statistics, operations research, and scientific computing. Very few new PhDs from pure or applied mathematics departments included in Group I or II (Jones et al., 1982; see also AMS, 1988, *Notices,* **35** (April), 532–533) found industrial employment.

The shortage of opportunities for postdoctoral positions in the mathematical sciences makes postdoctoral study an unlikely next step for many new PhDs. Federally supported postdoctoral positions in the mathematical sciences totaled 188 in 1988 (at which time there were 1280 federally supported postdoctoral positions in physics and 2587 in chemistry), and only one-half to one-third of these are available each year, enough to serve less than 10% of the new PhDs. Since many colleges and universities seek to make their tenure-track appointments to individuals who have completed a postdoctoral fellowship, the paucity of such fellowships reduces the opportunity for the many other excellent candidates.

5

FOCUSED, REALISTIC MISSION

Successful programs have a focused, realistic mission. A program that has clearly defined goals, usually of a limited nature, is said to have a focused mission. A program that (1) educates doctoral students and/or postdoctoral associates for the jobs available to them after leaving the program and (2) can actually be carried out given the available human and financial resources is said to be realistic. Agreement on the mission by faculty, administrators, postdoctoral associates, and students is crucial. The mission must be consistent with the strengths of the faculty, and there must be adequate resources for the program, including a technical library, computer facilities, financial support by the university administration, a strong faculty, and, most importantly, doctoral students and postdoctoral associates capable of meeting the expectations of the program.

In this chapter and throughout the report, "model" means a "program with a focused mission." Site visits were carried out at programs that fit into the first four of the five models—standard, subdisciplinary, interdisciplinary, problem-based, and college-teachers—discussed in this chapter. The college-teachers model, which was known to committee members from other sources, is included for completeness and because of the growing emphasis on undergraduate mathematics education.

STANDARD MODEL

The "standard" doctoral/postdoctoral program in the mathematical sciences at American universities is modeled on the doctoral/postdoctoral programs at traditional, pre-World War II, European universities. It supports research in a broad range of areas, with depth in each one. The goal is to prepare talented, well-motivated doctoral students and postdoctoral associates for careers as mathematical scientists at research universities.

Many standard doctoral/postdoctoral programs assume that they will instruct the best students in advanced mathematics, that natural selection will ensure that those sufficiently able will write theses, and that the best of these will take positions at research universities and do research. And the cycle will repeat itself. This approach gives too little formal recognition to the fact that there are undergraduates to teach, that the graduates of the programs teach in colleges or secondary schools, and that positions in government laboratories, business, and industry require applications of the mathematical sciences. In other words, the current multifaceted responsibilities of the profession are all but ignored. This description is, of course, an exaggeration of the views that many have toward their graduate programs but, in many cases, not by much.

> The principal goal of the graduate program is to produce academic mathematicians. When pressed, some faculty acknowledged that employment out of academia did not absolutely indicate failure, but the bias was apparent. Unfortunately, not many recent graduates have obtained high-quality positions in academe, and that fact is bemoaned by faculty and students alike.
>
> Committee Site Visit Report

Most standard programs do well in preparing their best students and postdoctoral associates for the academic research job market, but very few prepare any of their students well for jobs in teaching, government, business, or industry. In the current tight academic employment market, a program that attends to the larger needs of its students may find that its graduates succeed in obtaining employment, whereas programs with a narrower focus may have graduates who experience difficulty.

> The faculty come from prestigious research institutions and feel that their mission is to train graduate students to do research. This leads to some frustration on the part of the faculty, who lament a rather weak applicant pool and struggle to maintain the standards they consider vital to the credibility of their research enterprise.
>
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In a standard program, research and study are viewed as solitary activities. Unless the program is very large, it is likely that there are only one or two professors in each area. Students may carry out their research without the benefit of interaction with a group of other students and professors working in their area of interest.

Most doctoral programs at American universities began by adopting the standard-model. A number of these programs struggle because they cannot attract the graduate students necessary to function as a standard-model program. The committee believes strongly that a successful program based on an alternate, specialized model, four of which are mentioned below, is highly preferable to a struggling, unsuccessful standard program. The health of the profession will always depend partly on well-established standard programs at a small number of centers. The committee believes, however, that efforts to broaden experience and provide a more supportive learning environment would improve these programs also.

SPECIALIZED MODELS

Subdisciplinary Model

In the subdisciplinary model, the department concentrates much of its faculty and resources in a few subdisciplines of the mathematical sciences. This can be done in both pure and applied areas. Recruiting strong, well-prepared students for subdisciplinary programs requires considerable effort to ensure a proper fit. The main advantage of the subdisciplinary model is that clustering of students and faculty working on related topics enables them to assist each other in their common goals.

> The most successful circumstances seemed to be those in which there was a coherent group of faculty with closely related research interests and active seminars. In such cases their students became part of a cohort of students who could give some critical attention to each other's work. As in many other situations, the creation of some kind of social bonding seemed to greatly enhance the quality and effectiveness of the work environment.
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Some of the doctoral programs with the best reputations for research are subdisciplinary programs. A smaller department is more likely to be successful if it adopts the subdisciplinary model or one of the other three models outlined below.

Interdisciplinary Model

While a subdisciplinary program often consists of a whole department, an interdisciplinary program is usually only one among several programs in a department of mathematics, statistics, or operations research. It utilizes department faculty with interdisciplinary interests and mathematically oriented faculty in cognate disciplines. The curriculum, which often involves course work in one or more other departments in science or engineering, trades depth in the mathematical sciences for greater breadth overall. Students can choose thesis advisors from the mathematical sciences department or the other department. Faculty in both departments often adopt a cooperative approach to directing PhD research.

The strong esprit de corps that is usually part of such a program can be used effectively to recruit higher percentages of domestic students and to increase the PhD completion rate. Women and minorities are often successful in interdisciplinary programs because of this positive atmosphere.

Graduates of interdisciplinary programs sometimes move into other disciplines or take positions in industry. These programs succeed in bringing mathematically well-trained students into fields in which they can effectively use their talents and at the same time promote the transfer of mathematical knowledge to these fields.

Problem-based Model

In a problem-based model, a specific application or set of applications is used as a unifying theme for courses and research. Unlike an interdisciplinary program, a problem-based program usually concerns itself with the strictly mathematical aspects of an applied problem. Mathematical modeling is a common focus in a problem-based program. The committee observed programs in discrete modeling for economics and social sciences and in continuum modeling for engineering. All of the problem-based programs visited by and known to the committee concentrate on applied areas of mathematics, statistics, and operations research, but a problem-based program in pure mathematics could be set up. The problem-based programs that the committee visited concentrate on the training of professionals knowledgeable in applications of value in academia and in industry.

An attraction of the problem-based model is that the students are immersed in research-related activities from the beginning. Student internships in regional industries are often an integral part of this kind of program. Industrial researchers often visit the department. Post-PhD employment opportunities in industry are common, but graduates also obtain positions in academia.

College-Teachers Model

The college-teachers model is designed to prepare teachers at two-and four-year colleges. A college-teachers program is to be distinguished from a program that confers doctor of arts or doctor of education degrees. Breadth of course work and an emphasis on professional development in pedagogy are, in addition to a research apprenticeship, parts of such a program. Most new PhDs from standard programs currently take jobs in college teaching but are often ill prepared for their teaching duties. New PhDs from a college-teachers program are attractive candidates for employment at four-year colleges because they are prepared to be teachers. The need for college-teachers programs could increase as the need for college faculty increases toward the end of the 1990s and into the next century.

Common Features of Specialized Models

Two human resource problems, recruitment and placement, are alleviated by having a specialized program. The specialized programs that the committee observed were able to place their graduates in appropriate jobs more easily than standard programs. In recruiting domestic doctoral students, postdoctoral associates, and junior faculty, specialized programs must be careful to pick the "best" candidate only if he/she fits into the areas of specialization of the program. Nevertheless, specialized programs are typically able to recruit domestic students, including women and underrepresented minorities, more effectively than standard programs, partly because of their ability to articulate their mission and place their graduates effectively. Placement is easier because, as the committee saw in its site visits, many specialized programs maintain close contact with regional colleges and industry as well as with former graduates. Industrial internships are a prominent feature of many of these programs, especially those in statistics and operations research.

Although the education in interdisciplinary, problem-based, and college-teachers programs is typically broader than that provided in standard programs, the depth can be somewhat less. This seems not to cause problems for students taking positions in industry or four-year colleges, but graduates seeking permanent positions at research universities sometimes need to further their education in a postdoctoral position.

More than simply alleviating human resource problems, the focused mission of a specialized program also promotes clustering of faculty, postdoctoral associates, and students, which helps create a positive learning environment and promote relevant professional development.

In the doctoral and postdoctoral system of mathematical sciences education in the United States, both standard and specialized programs are needed in theoretical as well as applied areas, and all of these kinds of programs can be successful. However, programs that do not have the human or financial resources to run a successful standard program should consider whether a specialized model might better fit their needs.

6

POSITIVE LEARNING ENVIRONMENT

Doctoral students need feedback and encouragement provided in a cordial atmosphere. Many talented students, uncertain of their talents, leave doctoral programs for want of reassurance or fail because feedback is too intimidating—outcomes that a positive learning environment can help prevent. In a positive learning environment, all students are viewed as potentially successful.

How does a program create a positive learning environment, that is, an environment that provides the assistance, encouragement, nurturing, and feedback necessary to attract and retain students and to give them an education appropriate for their future careers? Perhaps the most important step that a department can take is to cluster faculty, postdoctoral associates, and students in specialized areas, as indicated in Chapter 5. Clustering has been common in other sciences and engineering for a long time but has only recently been advocated in the mathematical sciences. Although mathematics is an individual activity and scholarship requires time spent alone, doctoral students and postdoctoral associates benefit from opportunities to discuss, to ask questions, and to try out ideas on interested and knowledgeable colleagues. They must learn to communicate mathematical ideas as well as to discover them, both of which require regular social and intellectual interaction.

Clustering of students becomes increasingly important as the courses and research experience of the students become more specialized. Even when the student has a thesis advisor as his/her principal research mentor, the student still needs to be part of a group of students, postdoctoral associates, and faculty working in the area.

> The department, while large as math departments go, nonetheless concentrates its strength in certain distinct areas of research without trying to cover the waterfront. Consequently a dissertation student is teamed not simply with a thesis advisor, but also with an active cluster of faculty and students with related interests, involvement in ongoing seminars, and strong interactions.
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COMMUNICATION AND COOPERATION

Effective communication is vital to a positive learning environment. Students need to know how the system works, how and when they will be evaluated, and how decisions are made regarding academic progress and financial support. An orientation meeting for new students and a booklet summarizing the program are useful. Also important is a sense of the faculty's being accessible.

> The graduate students showed extraordinarily high morale and cohesiveness, and a shared ethic of hard work and high performance. Students repeatedly testified to the concern and accessibility of the faculty and to the mutual support and concern of the students for each other. There was remarkably little evidence of the ill effects of student competitiveness that one finds in many other programs.
>
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> The principal attraction for the great majority of students, beyond the reputation of the program, is the friendly, open, cooperative, non-competitive atmosphere. The instructors are approachable, and the students form study groups that are gender-integrated.
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The factors that lead to success in attracting and retaining women and underrepresented minorities are the same as those for domestic students in general: a strong and focused mission, a positive learning environment, and relevant professional development. The positive learning environment seems to be the most important of these three factors.

> The atmosphere is quite inspiring, because the entire department seems to share a common philosophy. There is little talk about standards, but rather a positive, upbeat atmosphere that seems to foster confidence, professionalism, and mutual support among the students, particularly the women and minorities.
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Having the offices of faculty and students in one location and providing a “commons” area both encourage an open atmosphere.

> Their major problem is that they are not provided with office space and thus have little opportunity to interact with other graduate students, especially in the evening.
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Communication with colleagues as well as about a program's requirements and procedures is also important for postdoctoral associates and junior faculty. They need to understand clearly the terms of employment, including what is expected of them and when and how decisions will be made on reappointment, promotion, and tenure. Junior faculty need feedback as well as encouragement from senior faculty. It is important for the chair of the department to meet regularly with them.

EFFECTIVE ADVISING

On the basis of previous academic record and placement examinations, all incoming students should be placed in courses of an appropriate level. Remedial courses should be prescribed where necessary. “Blanket” solutions to the problem of underpreparation of domestic students that are perceived as not being based on the performance of the students may not succeed. For example, one program that the committee visited set up a “zeroth year” for all students without previous graduate study, a category that includes most domestic students, but it has had little success in recruiting students into it.

The committee observed that, in some larger standard programs, a “Darwinian struggle” is characteristic of the first two years, with the faculty accepting only the survivors and the graduate students being guided only minimally in their course work and in their learning how to perform research. In such programs, many faculty members do not exhibit concern about whether graduate students actually finish their degree programs. The seriousness of the problem is underscored by the fact that, in the mathematical sciences, only 1 out of 20 graduate students achieves a PhD, whereas in the physical sciences, 1 out of 10 graduate students receives a doctorate (NRC, 1990b).

All students need to be advised about courses and research opportunities available in a department and about the expectations of the department. Advising on entrance to the program helps students to select courses of an appropriate level and to understand the program. During subsequent years, advising should point students toward the required exams. When the interests or abilities of a student do not match the mission or expectations of a program, other possibilities such as transferring to another program or career changes should be suggested. Many students can and do succeed when placed in a more suitable program. Attrition, if it occurs, should occur early.

> It is during the first two years that an appropriate framework is most important, for it is here that a decision will usually be made as to whether the student is to continue for the PhD or not. An experienced supervisor will probably have little difficulty in deciding by the end of this time, but the student must be able to see the decision as just and fair, as indeed so must others working in the same department. (CGS, 1990, p. 3)

> Because of the difficulties of selection, it is imperative that doctoral programs evaluate students' progress, identify those students who should make other career choices, and help students who are experiencing correctable problems. Where attrition occurs unnecessarily, students have been mistreated. When attrition occurs unnecessarily deep into the program, students, faculty, and institutions are expending resources to little or no good purpose. (AAU, 1990, pp. 9–10)

For advising to be successful, its importance must be recognized. Programs must make certain that enough faculty act as advisors, especially for entering students. Additional effort to ensure thoughtful advising can lead to higher morale and more efficient use of time and resources. The tendency in some programs to saddle the same small group of faculty with responsibility for advising beginning graduate students is shortsighted and can be very costly to the program down the line.

> Students get lost in the shuffle, and supervision and counseling are often deficient. This affects both the first-year students, many of whom are vulnerable and in need of some confidence building, and later also some of the dissertation students.
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COURSE WORK AND SPECIALIZED STUDY

Course work is a necessary part of an American doctoral program because most students are not adequately prepared in basic mathematical sciences to proceed directly to research when they start graduate school. Although the horizons of the mathematical sciences have been expanding over the past 50 years, many standard doctoral and postdoctoral programs have continued to focus only on traditional core subjects. In these programs, students are often fit into rigid classical programs based on the specialized research interests of the faculty. As a result, the doctoral curriculum at many institutions lacks sufficient breadth to enable the graduates to teach basic undergraduate mathematics in an effective and innovative manner. The number of mathematics courses taught outside of mathematics departments at the advanced undergraduate level exceeds those offered within mathematics departments. According to one recent report, more (173,237 as compared to 147,000) students are taking advanced work in mathematics outside of mathematics departments than within (Garfunkel and Young, 1990).

Graduates are also often unable to engage in interdisciplinary work as a member of a team. Students who limit their studies to mathematics departments are often ill prepared to take positions in industry. Such jobs are often held by people in science or engineering with liberal amounts of mathematics training. To achieve broader experience, students may need to look outside of mathematical sciences departments. Students can be encouraged to take courses, even at the undergraduate level, in other departments to become familiar with applications. Equally important, beginning course work in the mathematical sciences must be at a level appropriate for the students in the program, and remedial instruction for underprepared students should be provided to fill gaps.

Advanced courses and research-level courses are critical for students not merely in reaching the frontier of their specialty but also in choosing a thesis advisor. Student seminars with active faculty participation can be a very effective addition to advanced course work. Students in such a seminar can learn the material in an active way and also learn how to communicate it. Specialized study in one or two areas just before research on the dissertation is begun should involve course work, seminars, and individualized study. Clusters of students working in the same area are increasingly important at this stage. Programs in which faculty direct this specialized study find that the often-difficult task of pairing students with thesis advisors is thereby eased.

EARLY RESEARCH EXPERIENCE

In a standard-model PhD program in the mathematical sciences, research experience is usually postponed until after the second qualifying examination. Most doctoral programs in other sciences and engineering provide exposure to research much earlier. Students work in groups or clusters with academic researchers as a part of a team.

> Beginning graduate students in the laboratory sciences may learn as much from advanced graduate students and postdoctorals as they do from the principal investigator—the group provides a mutually supportive and nurturing learning environment for all. The challenge for the mathematical sciences is to create an analogous environment for their own graduate students and postdoctorals. (NRC, 1990c, p. 64)

Early research experience through problem solving, experimentation, or computation gives students a better idea of how to create and apply mathematics and often provides additional motivation. Many of the specialized programs visited by the committee provide early research experience to their students and, partly because of this, have high completion rates. The committee believes that all doctoral programs, both pure and applied, would benefit from integrating opportunities for early research experience into the program.

MASTER'S DEGREE PROGRAMS

Viable professional master's degree programs in pure and applied mathematics are not common in the United States. Master's degrees granted in standard doctoral programs are often considered consolation prizes for students unable to achieve a doctorate. This is in contrast to the situation in Europe, where a master's degree (*Diplom, diplôme*)in mathematics is a valued professional degree.

A professional master's degree program would be an excellent complement to a doctoral program. Such a master's degree program could have one of the specialized missions described in Chapter 5. It could be an excellent means for students to gain confidence in their ability without committing themselves to an open-ended doctoral program and would be attractive to them because of the value that government, business, and industry could place on a properly structured and specialized professional master's degree. Some PhD students in engineering and social sciences earn master's degrees in mathematics or statistics to raise their status. A professional master's degree program could be an important source of doctoral students who might otherwise choose to study some other discipline. Finally, a professional master's degree program can provide through its alumni excellent ties to industry and to elementary and secondary education. Appendix C describes how professional master's degree programs could enhance doctoral programs and fulfill needs for mathematical sciences personnel in government, business, and industry.

QUALIFYING EXAMINATIONS

The first qualifying examination sets the tone for the rest of the predoctoral period. Currently, it often has a negative effect even on those students who readily pass the exam. Sometimes it is viewed by all as the gate to keep out the unworthy, those who should not have been admitted to a program in the first place. In standard-model programs, the examination is often based on a limited number of traditional areas that are not necessarily connected with the student's area of future research.

> The first exam is seen by first-year students to be a formidable hurdle, with high mortality. It is a source of considerable anxiety, and many students felt that there is insufficient counseling and support given by the department in the first year.
>
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> It does not, however, appear possible to receive a broad education in applied mathematics. The first exam is based entirely on core areas, a condition that prompted one applied mathematician to comment, “The program requirements are debilitating to applied mathematicians.” Some of the current fellowship holders commented that there is a “just you wait …” approach to the utility of mathematics, that “there is little or no contact with other departments,” and that “the faculty are disdainful of non-math courses ….”
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The mathematical sciences are broad, and the first examination should reflect that breadth in both core and applied areas. Core programs benefit from having applied areas represented in the examination. Programs specializing in applied areas should permit inclusion of some core areas on the first exam.

The first qualifying examination should be a diagnostic tool that assists faculty in deciding whether doctoral study is for specific students as well as to assist the students in making that same decision for themselves and in determining whether they are ready to proceed or need additional time and study. Most students who put forth sufficient time and effort should be able to pass the examination, and the faculty should be there to assist. The committee was amazed at how such an approach can transform a doctoral program, an approach that need not be inconsistent with the other purpose of the first examination, namely, to assist students in deciding whether doctoral study is for them. Making assistance and guidance available to students studying for the first qualifying examination can have very positive results.

> A useful support instrument is a first exam workshop, set up by advanced students, which runs group problem sessions for first-year students. These workshops have been extremely valuable, not only for their instructional content, but also as a setting in which students get to know each other more informally.
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The second qualifying examination can be written or oral but should involve more than one faculty member. This examination certifies that a student is ready to start work on a dissertation. It should permit specialization in the direction of the future research of the student.

> The second exam is an oral exam, based on a topic selected by the student in consultation with a faculty member that may, but need not, turn out to be the student's advisor. This system seems to reduce much of the anxiety usually associated with finding a thesis advisor, as the necessity to form a working relationship with a member of the faculty is built into the program at an early stage.
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RESEARCH AND THESIS

Mathematical sciences graduate students, like those in other science and engineering disciplines, are an integral part of the academic research enterprise. However, the faculty in standard mathematical sciences programs are less dependent on graduate students to sustain their research projects than are the faculty in the other sciences and engineering. In the mathematical sciences, research apprenticeships for graduate students before they begin work on a dissertation are not a standard part of the program.

When students reach the dissertation stage of their studies, advising is done by their thesis advisors. Currently in many standard programs, selection of a thesis advisor is an idiosyncratic process.

> Students must work to find a thesis advisor. There are almost no research assistantship inducements, and most faculty do not advertise that they are seeking or have room for a thesis student. Students often feel intimidated about approaching faculty members about their research. This is probably not due to excessive reserve on the faculty's part, but there is also very little outreach.
>
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By designating a faculty member as an advisor for specialized study and the second examination, a program can facilitate the process of matching a student with a thesis advisor. A program-sponsored forum for faculty to discuss their research interests can also help, as can opportunities for students and faculty to meet informally. A program should monitor both the research progress and the relationship between the student and the thesis advisor. The thesis advisor has responsibility for the progress made in the research of the student, including attendance and participation in colloquia and conferences. The thesis advisor also has responsibility for the student's professional development, including his/her learning how to communicate orally, how to publish, and how to teach.

> There are two aspects to supervision [by the thesis advisor]. The first and more important has to do with creativity and involves the ability to select problems, to stimulate and enthuse students, and to provide a steady stream of ideas. The second aspect is concerned with the mechanics of ensuring that the student makes good progress. (CGS, 1990, p. 1)

Although the thesis advisor has primary responsibility for the student completing the dissertation, the program also has a share. In addition, the student still needs to be part of a cluster of students, postdoctoral associates, and faculty working in the same area. The time necessary to move through the various stages of a doctoral program varies from student to student. Flexibility in time requirements is important, often critical, to students with family or other obligations.

When more is expected of students and when assistance in reaching the higher standards is provided, students achieve more.

> At the dissertation stage nothing should be done to diminish the necessary rigor of the research apprenticeship, but much can be done to minimize unnecessary frustration and to improve the process. (CGS, 1991, p. 32)

The thesis defense should be used to demonstrate a student's expertise and to show other students the level of expectation and accomplishment in the program. Attendance by faculty in addition to the appointed committee is important.

> For the student, the defense should be a "crowning experience," the ultimate opportunity to demonstrate his or her expertise after years of research, reporting, and writing. It is also excellent preparation for future professional presentations where defense of one's work is an accepted part of standard professional meeting structure. For other doctoral students who attend the examination it is a learning experience, conveying guidance on the formulation and completion of a dissertation project. (CGS, 1991, p. 28)

POSTDOCTORAL FELLOWSHIPS

Education does not end with completion of a PhD. It is very useful to the new PhD and to society in general to extend the learning period by a few more years. However, the opportunities to do so in the mathematical sciences are limited. The number of postdoctoral positions available to mathematical scientists is far below those available in the other sciences. In 1988, there were only 188 federally funded postdoctoral positions in the mathematical sciences vs. 1280 in physics and 2587 in chemistry (NRC, 1990c). In the physical and biological sciences many new doctorate degree holders seeking an academic career start with a three-year postdoctoral position, most often federally supported. This position is viewed as the logical next step after completion of the doctorate for the good student, not as a highly competitive prize for a select few. In the mathematical sciences, postdoctoral fellowships are viewed as prizes for the very best rather than as a logical next step in research for many new doctorates, so that mathematics PhDs from American graduate schools that are not among the elite included in a postdoctoral-fellowship or research/instructorship program are often left woefully unprepared to compete with new PhDs from abroad.

The restricted opportunity for postdoctoral education in the United States contrasts sharply with the practice in the European mathematical community. Although European undergraduates specialize earlier than their American counterparts and hence know more mathematics when they begin graduate study, many European countries still provide an extended research apprenticeship program for new PhDs to deepen their research experience.

The problem of limited opportunity for postdoctoral education is compounded by the fact that departmental committees selecting postdoctoral associates often focus on attracting the best new doctorates, independent of a candidate's field.

> The "postdocs" are appointed predominantly on the grounds of scientific achievement, independent of field. As a result many of them arrive with no natural scientific bonds within the department.
>
> Committee Site Visit Report

Such an approach often results in a lonely, isolated tenure with limited departmental interaction and little if any "postdoc"-mentor relationship with the senior faculty. Postdoctoral associates should be hired in the areas of expertise of the program, not in other areas. Each should have a mentor from the senior faculty and be a member of a group of faculty, postdoctoral associates, and doctoral students working in the same area.

The postdoctoral positions that are currently available are usually designed to deepen knowledge in a specific area of research. One could design postdoctoral fellowships that could be used to advantage to broaden the knowledge base of the fellow or to expand the fellow's expertise in teaching or applications.

The shortage of opportunities for postdoctoral positions places added responsibilities on departments to help new faculty who have not had a postdoctoral fellowship to continue growing toward their full potential. This is especially true for new faculty with temporary appointments.

A POSITIVE LEARNING ENVIRONMENT FOR ALL PROGRAMS

The clustering of faculty, postdoctoral associates, and doctoral students that typically takes place in a specialized program is highly beneficial for the learning environment. Nevertheless, all doctoral/postdoctoral programs, including standard programs in core areas, can achieve a positive learning environment and can benefit from it.

7

RELEVANT PROFESSIONAL DEVELOPMENT

As a rule, the professional development provided by current doctoral and postdoctoral programs is appropriate for positions at research universities. However, only a small fraction of new PhDs and postdoctoral associates spend their careers at research universities. Most pursue careers in environments quite different from that of a mathematical sciences research department. The majority of new PhDs devote much of their professional lives to teaching undergraduates. An increasing number take positions in government laboratories, business, and industry. Some become involved in pre-college mathematics.

Currently, new PhDs are typically not provided with the professional skills they need for teaching or for work in government R&D, business, or industry. However, in some programs, particularly in many specialized programs, professional development relevant to such positions is provided to the students.

TEACHING SKILLS

A large percentage of new PhDs, including those from the strongest programs, take positions in which teaching is their principal professional responsibility. However, little time is spent teaching them how to teach.

> A surprising number of students (well over half) who were asked about their interests said they were interested in "teaching," "teaching in a four-year college," or "curriculum development" in secondary schools. There is no formal notice taken of these interests.
>
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Because most programs currently support most of their students by making them teaching assistants, these students do have some teaching experience. However, using graduate students as teaching assistants and giving them experience as teachers in a classroom are not the same as training them to be teachers. It was the committee's observation that more structured guidance is needed on how to teach.

> During the long years of work toward the doctoral degree, the candidate is rarely, if ever, introduced to any of the ingredients that make up the art, the science, and the special responsibilities of teaching. Yet, the major career option for most holders of the PhD degree is full-time teaching in a college or university. (AAC, 1990, p. 35)

> Few universities recognize explicitly in the design of their graduate mathematics programs that the future careers of most of their doctoral students will be devoted primarily to undergraduate teaching. Few if any mathematics graduate programs attempt to familiarize graduate students with important curricular and policy issues of undergraduate education. Few graduate assistants undergo systematic training to prepare them for their lifelong role as teachers. (NRC, 1991b, p. 27)

It is important that all students, especially future educators, have the opportunity to receive instruction on how to teach and to have supervised experience in teaching.

> The Department … will develop a seminar for third and fourth year PhD students on [what is involved in] becoming a college professor.
>
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> Departments and programs should assure that their graduate students receive instruction in teaching methods, with assessment and feedback on teaching performance and, if possible, with a progression of increasingly advanced teaching experiences including significant in-class teaching. (AAU, 1990, p. 4)

COMMUNICATION SKILLS

Professional mathematicians also need communication skills for non-classroom settings, skills such as how to conduct seminars, give professional talks, interact with people working in other sciences and in engineering, and communicate mathematical ideas and results to others in applied/industrial teams. Having students conduct their own seminars is a useful tool for helping them learn how to give professional talks.

> One feature of the department's offerings is a course fondly termed the “torture chamber.” This experience, required of every student, is designed to prepare the student to give polished professional talks in her/his field. Faculty provide criticism (considered constructive by the students) and encouragement, and students talked about it with a mixture of dread and admiration.
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Not everyone is gifted with natural communication skills, but practice and work can lead to improved skills. As much or more than colleagues working in academia, mathematical scientists working in industry need to know how to communicate their knowledge and discoveries.

> I have often heard, "My student can't lecture so he/she should consider an industrial job." This is perhaps the biggest misconception about a non-academic career. Communication skills are even more important outside of classrooms. An industrial researcher interacts with a wide variety of people including engineers, computer scientists, physicists, chemists and business people. The effectiveness of one's work depends on the ability to convey the power and impact of mathematics as well as its beauty and elegance. It is quite possible to explain mathematics in general terms to non-experts. Even a good colloquium talk involves several different levels of depth. Successful communication not only transfers knowledge and insight helpful to others but also brings up good problems, new directions and interesting ideas. (Chung, 1991, p. 560)

TEACHING ASSISTANTSHIPS

Of the full-time mathematical sciences graduate students in 1987, 57% were supported by teaching assistantships, whereas in the physical and biological sciences and in engineering, only 24% of the graduate students were dependent on teaching assistantships for support (NRC, 1990c). This imbalance is due to the lower level of research funding for the mathematical sciences vs. that for the other sciences and engineering, as well as to the service role that has been imposed on mathematical sciences departments. Nevertheless, since teaching is the main professional activity of most students who receive the PhD, better use could be made of teaching assistantships to teach students how to teach.

> Graduate students teach too much but are not sufficiently assisted in becoming effective teachers; we find this both ironic and unacceptable. (AAU, 1990, p. 3)

Although most universities normally limit the duties of teaching assistants to 20 hours or fewer per week, some departments still have unrealistic expectations, often neglecting to take into account all duties, including preparing for class, holding office hours, writing, giving and grading exams, and attending instructor meetings.

> Students felt that their teaching assistantship duties were consuming more than the nominal 20 hours a week. TAs are asked to teach their own courses and, in addition, grade one of the faculty's classes or participate in research. The time pressures are such that students are reluctant to register for more than two courses per semester. This stretches out their program and leads, in turn, to students running up against the limitation on how much time students are supported.
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Departments sometimes fill graduate teaching assistantships to meet the teaching needs of the department, often with students who have little hope of getting a master's degree, let alone a PhD. This practice is not only wasteful for the students involved but also detrimental to program morale.

Students should be given responsibilities that reinforce their studies and promote progress toward their degrees. The total number of hours of teaching duties should be limited to 20 or fewer per week so that teaching does not interfere with academic progress. The department should make it clear that the study of mathematics is the primary activity and should design its program to accord with the philosophy that

> [t]he primary reason why graduate students should teach is to prepare them to be effective teachers. (AAU, 1990, p. 3)

THE NON-ACADEMIC MARKET

To prepare graduate students, postdoctoral associates, and temporary faculty for non-academic career paths, programs must provide greater breadth of mathematical experience, which often means including statistics, computational mathematics, or operations research. Students also need to learn and to speak the languages of the disciplines to which the mathematical sciences are applied. The committee visited programs that were very effective in fostering such an approach. Some of these programs had close ties to regional industry.

More mathematical scientists with the PhD should learn mathematics relevant to computations, applications, or interdisciplinary problems so as to fulfill needs for the mathematical sciences in the U.S. technology base.

> From engineering design and research to management and organizational structures to the control of smart machines and robots, the computer is leading a revolution that vitally affects the competitiveness of industry and of our entire society. The mathematical sciences are at the basis of many of these changes, and they provide a crucial technology in effecting this revolution. (NRC, 1991a, p. 7)

Computational fluid dynamics, medical scanning technology, spatial statistics, remote sensing, and environmental monitoring are but a few of the areas of applications of the mathematical sciences. These and many other areas (NRC, 1990c, App. B; NRC, 1991a) provide growing opportunities for appropriately trained mathematical scientists. Industrial connections in these areas can lead to support for students, consulting for faculty, jobs for new PhDs, and solutions to problems of economic interest to business and industry. The committee saw many successful examples of good working relationships between mathematical sciences programs and industry in its site visits.

> The department has so many contacts with industry. . . .Industrial recruiters visit the campus and many students take industrial positions.
>
> Committee Site Visit Report

THE POSTDOCTORAL EXPERIENCE

The postdoctoral experience of every new PhD, whether as a postdoctoral associate or a young faculty member, should include time for research. Understanding research and its role in the mathematical sciences is important for anyone doing, applying, or teaching mathematics. Research experience after receiving the PhD is appropriate experience for all careers. Such experience is most appropriately gained in a postdoctoral fellowship at a research university but, due to limitations on funding, may be gained in a research instructorship or term position at a research university. The need for a continuing research apprenticeship in the postdoctoral period reflects the breadth and complexity of the mathematical sciences. Research during the postdoctoral period should be viewed as the logical next step after the doctorate. The committee observed that clustering of postdoctoral associates and junior faculty with senior faculty and graduate students as well as the continuing guidance of a mentor for each postdoctoral associate or junior faculty member are particularly effective in promoting professional growth in research.

The postdoctoral experience should include development in other areas also. Currently, nearly all postdoctoral fellowships are oriented toward doing research alone. Interdisciplinary but mathematics-based postdoctoral fellowships, only a few of which exist, are a way of broadening the fellow's scientific outlook. It would be appropriate to introduce professional development components—teaching or applications— into many more postdoctoral fellowships. Such fellowships could form a bridge to future careers in which teaching or applications are important. A postdoctoral fellowship should be considered to be one step in continuing, lifelong professional development.

8

TOWARD MORE SUCCESSFUL PROGRAMS

This country's emphasis on science and technology, coupled with generous federal funding, attracted some of the best students to the mathematical sciences during the 1960s and early 1970s. Standard programs worked well then. Today, the pedagogical and technological needs of U.S. society are larger, the available funding is less, and the competition for the human resource pool is more intense. But prudent, thoughtfully introduced changes in doctoral and postdoctoral programs can result in more of the best undergraduates again choosing careers in mathematics rather than in computer science, business, law, or medicine.

The health of the mathematical sciences will always depend on having a number of standard programs that offer highly selective doctoral and postdoctoral programs. The observations and recommendations in this report apply to these programs as well as to other departments. However, many departments that do not have the human or financial resources to have a successful standard-model program nevertheless attempt to follow the standard-model. As a result, many capable graduate students do not get a PhD. Those who do are prepared for a career of research, yet only 1 out of 10 PhDs in the mathematical sciences makes a published contribution to mathematical research. (Additional contributions to research in other areas are made by mathematical scientists who have moved into substantive work on applications.) The many PhDs who become full-time teachers after receiving the PhD have often not been given instruction on how to teach effectively. The ones who work in government and industry are often ill prepared for work in applications and do not have well-developed communication skills.

The goal of U.S. doctoral and postdoctoral programs in the mathematical sciences should be to provide the well-trained people necessary to meet the needs of all of the mathematical sciences—pure mathematics, applied mathematics, statistics, operations research, and scientific computing—for research, teaching, and work in government laboratories, business, and industry. Teaching involves the instruction of all students, mathematics majors and others, and includes partial responsibility for pre-college instruction and continuing education.

A high-quality faculty is necessary for a successful program, but it is not enough. A focused and realistic mission, a positive learning environment, and relevant professional development are the ingredients that create success. The best undergraduate students with strong mathematical backgrounds can choose to continue their studies in the mathematical sciences, the physical sciences, engineering, law, medicine, or other areas. But a larger portion of the best domestic students can be induced to study the mathematical sciences if a program recruits aggressively and also provides a positive learning environment and relevant professional development.

> The department has been successful in attracting many domestic students because of its vigorous recruitment in small regional colleges, the warm atmosphere, the renown of the program, the availability of adequate financial aid, and a reputation for placing people in excellent positions on graduation.
>
> Committee Site Visit Report

The current U.S. system of doctoral and postdoctoral education was created by the combined efforts of the faculty, departmental management, collegiate administrators, and the federal agencies with influence by students and, to some extent, by society. The efforts of these groups have been fundamental not only in creating standard-model programs but also in creating specialized programs. If changes are to occur, the ideas suggested in this report implemented, and new programs created to meet the needs of our technological society, all of these groups will need to cooperate, agree on goals and missions, and find the necessary resources.

FACULTY AND DEPARTMENTS

A key to all doctoral and postdoctoral programs is the faculty. No program can function without the support, cooperation, and whole-hearted backing of the faculty. Any attempt at assessment and change must involve the faculty from the start.

The first step for a mathematical sciences program is an assessment of how well it is functioning. All universities collect data, and some of the necessary information will be available. Many universities conduct periodic reviews of departments and programs through outside teams, whose reports can contain valuable information. It is important to factor into the planning process realistic estimates of the human resources—students and new PhDs—available to the program. The questions about mission, learning environment, and professional development posed in Appendix A may prove useful. The assistance of faculty who are not currently involved in administering the program or department can provide an invaluable objective viewpoint. Involvement of the university administration in the process can have benefits during the implementing of decisions once they are made. Soliciting feedback from institutions that will employ the graduates of the program—colleges and universities, government, and industrial organizations—is useful.

After the assessment is complete, the faculty and the department should decide whether the current mission for the program is appropriate or a new mission should be developed. Unless resources are sufficient to permit implementation of a standard mission/model with coverage of a broad range of areas, a more specialized mission should be devised that better fits the resources available. Determining the mission first is important, because many aspects of the learning environment and professional development depend upon the particular mission—for example, how the learning environment and professional development should be oriented will depend on whether the program is designed to emphasize teaching or industrial applications.

Once the mission has been established and the structure set for the learning environment and professional development, recruiting procedures of the kind mentioned in Chapter 4 can be used. Systematic recruiting of undergraduates at colleges and other universities as well as at one's own university does not merely reapportion the pool of candidates. It increases the pool.

PROFESSIONAL SOCIETIES

Doctoral and postdoctoral education has been a topic at meetings of some committees of the mathematical sciences professional societies. However, no professional society currently has a standing committee devoted solely to this topic. A standing committee—or perhaps three: one in pure and applied mathematics, one in statistics, and one in operations research—with ongoing responsibility for doctoral and postdoctoral education should be established. One of the activities of this committee should be to collect and annually publish statistics on doctoral programs, including statistics on completion rate such as the two types mentioned above in the introduction: (1) the percentage of students who entered a program five years earlier and who have received their doctorates, and (2) the percentage of students who completed their second year of graduate study four years earlier and who have received their doctorates. These statistics would assist departments in assessing their own programs and students in choosing graduate programs.

FEDERAL AGENCIES

Research support from federal agencies has been one of the foundations of the success of the mathematical sciences in the United States. In the past, this research support has usually been given without an assessment of its effects on doctoral and postdoctoral education. The new practice at the NSF of requesting information on the impact of a grant on doctoral and postdoctoral training is a step in the right direction. This information needs to be taken seriously in evaluating proposals and this policy extended to all federal agencies.

The GAANN grants recently instituted by the Department of Education have had the effect of increasing the recruiting activity of departments. Although some of this recruiting activity has resulted in merely reapportioning students to the universities that recruit actively, the long-term effect should be to increase the pool of students. The committee strongly urges continuing the GAANN Program at least until active recruiting becomes part of the community culture.

Another way to support doctoral/postdoctoral education would be to fund grants to support the mathematical sciences infrastructure. Block grants could be awarded to groups that include doctoral students and postdoctoral associates with the stipulation that a major factor in renewal would be the number and quality of the domestic doctoral and postdoctoral students produced by the group.

A program that combines the features of the NSF's Minority Predoctoral Fellowship Program and the Department of Education's Ronald E. McNair Post-Baccalaureate Achievement Program would be a powerful factor in increasing the number of women and minority undergraduate and graduate students in the mathematical sciences. Such a combined undergraduate scholarship/graduate fellowship program for women could work as follows. A grant equal (in dollars) to a graduate fellowship would be given to each woman selected and to her undergraduate department: the woman would receive a partial scholarship for her senior year valued at half of a graduate fellowship stipend, and her undergraduate department would receive a grant of equal value. Each woman would be obligated to major in the mathematical sciences. Each woman would receive, in addition, a two-year fellowship to pursue graduate studies in the mathematical sciences. Undergraduate departments would be motivated by this program to identify and encourage women undergraduates starting in their sophomore year, that is, at a time when many women are still in the mathematical sciences pipeline. A similar program could work for students from underrepresented minorities, but it would have to begin a year earlier. Few minority undergraduate students major in mathematics, but a substantial number do take calculus. Departments could identify the outstanding minority students in calculus classes and urge them to apply for such a scholarship/fellowship program in their sophomore year. Two years of undergraduate support of the same type as that for the senior year of the women's program would be needed.

The federal support for postdoctoral fellowships in the mathematical sciences should be brought into balance with that for the physical sciences; that is, the number of postdoctoral fellowships should be significantly increased, but without decreasing the number of senior investigators. This could be accomplished by increasing the number of postdoctoral fellowships in larger grants, so as to encourage stronger ties between the postdoctoral associate and the mentor. The recent track record of the mentor in working with postdoctoral associates, not just the quality of the research of the mentor, should be considered in the review of the proposal. The proposed mentor's evaluation of the relevance of the research of the postdoctoral associate should also be considered.

In order to provide a larger fraction of new PhDs with an opportunity for a postdoctoral fellowship, restrictions on new PhDs being supported for more than two years by postdoctoral fellowships, whether funded by federal agencies or universities, might be useful. The benefit that new PhDs receive from being postdoctoral associates at research universities is important enough that a larger fraction of new PhDs should have the experience. Postdoctoral fellowships should not be prizes for the few but should be, as in the physical sciences and in engineering, a next logical step for many qualified new PhDs.

THE KEY TO ACTION

Changing the American doctoral and postdoctoral system in the mathematical sciences so that it responds better to the needs of the profession, students, and the society is a task that requires the cooperative efforts of faculty, departments, professional societies, and federal agencies. The departments at research universities have a special responsibility to raise the level and increase the knowledge of talented but underprepared entering American doctoral students. Federal agencies should continue their programs and also increase their awareness of the impact of their programs on the doctoral and postdoctoral system. Professional societies should be involved in monitoring change in the universities, the agencies, and the community. But action, if it starts at all, will start from the faculty. The faculty should be aware that creating and maintaining a successful doctoral/postdoctoral program will require additional effort and time. The long-term benefits to the department, the students, and the society are clearly worth the effort.

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APPENDICES

APPENDIX A

DOCTORAL AND POSTDOCTORAL PROGRAM SELF-EVALUATION

The set of questions in this appendix is presented to assist departments in determining how their doctoral and postdoctoral programs are currently functioning and in what directions adjustments might be undertaken.

A. Faculty

1. What are the areas of strength and the areas of specialization in the department?
2. Are these areas unique or distinctive?
3. Do these areas fit together to create a deeper level of strength?
4. What are the connections of these areas with other disciplines and with industry?
5. How many faculty are involved in graduate instruction?
6. How many graduate courses are offered at (a) the introductory level, (b) the intermediate level, and (c) the frontier?
7. In addition to providing depth of knowledge in some areas, do the courses provide students with breadth of knowledge?
8. What proportion of student course work is spent in reading courses? Do such reading courses cause a significant overload for the faculty?
9. How many faculty are interested in and capable of directing theses? How many have done so in the last three years? Is there a capacity to direct more theses? Are the faculty who direct theses overextended?
10. Is there a significant difference in doctorate production between the various areas? If so, what are the reasons for this?
11. Is the size of the faculty likely to grow, remain stable, or decrease in the next 5 years? In the next 10 years? What impact will that have on how the preceding questions may be answered?
12. Given the anticipated dynamics (changing size, replacement of retirees) within the faculty, are there plans to redirect the emphasis and/or areas of specialty within the faculty? How will that affect the graduate programs?

B. Doctoral Students

1. How does the ratio of graduate students to graduate faculty compare with that of peer departments?
2. What proportion of graduate students enter directly into the doctoral program? What proportion enroll in a master's degree program? What proportion need to

take remedial undergraduate courses? Are the numbers decidedly different for U.S. citizens and non-citizens? Do any trends seem to be developing?

3. Are foreign students with more advanced experience permitted to take first-year courses solely to learn the English language or U.S. culture?
4. Over the last 10 years, what proportion of students who entered the doctoral program completed the doctorate? What proportion complete a master's degree? Do the successful PhD graduates work in only a few of the possible areas in which the program offers degrees? Is there a distinct difference in these numbers for U.S. citizens and for non-citizens? Are trends developing?
5. What is the length of time between receipt of the bachelor's degree and receipt of the PhD for the program's doctorate degree holders? If the interval is more than five or six years, at what point in the program, and why, do the delays occur? Have analyses been done to indicate how these delays might be reduced?
6. What happens to those who start the doctoral program and do not complete it? Are those who discontinue their studies doing so at the early stages, intermediate stages, or when beginning research? Are students who have little chance of completing the degree advised of this fact in a timely fashion? Are students who would find a better fit in some other department so advised? What direction and counsel as to continued study or employment are provided to those who discontinue their studies?
7. Do students in the program support one another or are they working as solitary scholars? Are the students in competition with each other?
8. Is there tension between students who are U.S. citizens and those who are non-citizens? Do they work together and share similar goals?
9. Ask questions 2, 4, 5, 6, and 7 for women students and students from underrepresented minorities.
10. Do students have opportunities to specialize in their areas of interest?

C. Recruitment of Students

1. Where does the program currently recruit its graduate students? What is the percentage of U.S. citizens among the graduate students? What would be the impact on the program if fewer non-citizens enrolled?
2. Are students told of the mission of the program when recruited? Is there an attempt to recruit students who have the same goals as those of the program?
3. Are the aspirations and ability of the students reasonably homogeneous? If not, how does the program deal with the variance?
4. Is there an active recruiting program? How effective has it been in recruiting students with the ability expected by the program's faculty?
5. Are there reasons to believe that a different recruiting program would lead to a student body more in accord with the program's aspirations?
6. Are any special efforts made to recruit women and minorities?

D. Support of Students

1. What proportion of the program's students are supported by teaching assistantships? By fellowships? By research assistantships? Is this mix appropriate?
2. Are graduate enrollments driven by the need for teaching assistants? Are teaching assistants evaluated on their teaching ability, their performance in the graduate program, or both?
3. Is the workload of the program's teaching assistants higher than that at peer institutions? Does it impede timely progress toward completion of the degree?
4. Do the students serve as teaching assistants longer than required to gain the teaching experience necessary for employment?
5. Is there a program to assist teaching assistants in developing their teaching skills? Do all students teach at some time? Do students learn from the faculty that teaching is important?
6. Does the program incorporate the means to develop and enhance a student's expository skills, both oral and written?
7. Is the library adequate to support the department's research activities?
8. Do students have convenient access to computer facilities adequate to their research and teaching needs?
9. Does the program have funding to assist graduate students in attending research conferences and workshops? Does the faculty encourage them to attend?
10. How do students in the program learn of professional standards and ethics? Should more be done?

E. Placement of Students

1. Does the department play a role in placing its graduates? Has it been effective?
2. Over the past five years, where has the program placed its PhD graduates? Master's graduates?
3. Is that placement in accord with the faculty's expectations and the goals of the program?
4. Has the pattern of placement changed from that of the previous five years? Ten years?
5. Did most of the PhD graduates find positions in keeping with their expectations? Were any underemployed? Did any fail to find employment within three months after receiving their degrees?
6. Does the employment pattern for U.S. citizens differ significantly from that for non-citizens?
7. Have any special efforts been made to make the department's non-citizen doctorates employable in the United States?
8. Are any special efforts made to place graduates in industry or government?

F. Programmatic Features

1. Does the program have a mission?
2. Do new faculty and graduate students understand that mission? Does it form a basis for recruiting faculty and students?
3. Given the faculty, the graduate students, and the resources available to the program, is the mission realistic? In particular, is there a good fit between the mission of the program and the graduate students' abilities and goals?
4. Does the university administration concur with the mission and does it provide sufficient funding to fulfill it?
5. Are the students given broad experience in the mathematical sciences and their connections with other sciences, engineering, and technology? Are the students provided with a foundation on which to build a 40 year career, one during which they may have to learn new fields and adapt to new job requirements?
6. Are the program's alumni professionally productive in a way consistent with the goals and aspirations of the program? What proportion of the alumni is active in research 10 years after receiving the degree?
7. Would some other mission or program structure be more appropriate given the faculty, the recruitable students, and the support for the program?

G. Postdoctoral Associates and Tenure-Track Faculty

1. Would a different mix of teaching assistants and postdoctoral associates better serve undergraduates and make for a stronger research environment?
2. Is there a program of terminal (two-to three-year) term appointments for new faculty? If so, how are such faculty selected? What are the goals and philosophy for the program?
3. Are postdoctoral associates and junior faculty included in the research and scholarly activities of the department? Does each have a mentor or senior support group?
4. Is the workload for postdoctoral associates and junior faculty such that they have time to develop their research capabilities?
5. Are the postdoctoral associates and junior faculty encouraged to assist in working with thesis students and with undergraduate majors?
6. Is the teaching experience of the postdoctoral associates and junior faculty designed so that they will grow as teachers?
7. Are the postdoctoral associates and junior faculty provided with the necessary library, computer facilities, and travel funds to meet their needs as researchers?
8. What assistance and direction are provided to junior faculty in seeking external funding?
9. Is it clear that postdoctoral associates and term junior faculty leave the program better prepared to function as professional mathematical scientists in their chosen

fields? Do they benefit from the experience or do they only serve to meet teaching needs?

10. Is there a program to place the postdoctoral associates and term junior faculty at the completion of their appointments? How effective has it been? Do they get placed so as to meet their expectations and those of the program?
11. Do junior faculty in tenure-track positions receive advice and direction about how to meet the conditions for promotion and tenure?

APPENDIX B

ADVICE TO POTENTIAL GRADUATE STUDENTS IN THE MATHEMATICALSCIENCES

Potential doctoral students are faced with around 300 programs in the mathematical sciences from which to choose. In which program should a student enroll? Students should choose a program based on its quality, its mission, its learning environment, and its ability to provide professional development. The quality of the faculty is often the only academic criterion used in the decision process. While the reputation of the faculty for producing quality research is important, it is not the only important factor. A quality faculty is necessary but not sufficient for a quality doctoral program. Doctoral programs at departments with faculty of comparable quality vary widely. In some programs most students complete doctorates and go on to rewarding careers in teaching and research. In others, few do.

It is essential for success in a graduate program that an entering student have a strong work ethic. Graduate schools expect from students a firm commitment that they will immerse themselves in mathematical sciences and that they are prepared to function at a high level. Undergraduates should take as many mathematical sciences courses as possible, choosing the more rigorous and demanding courses. Potential doctoral students should have a clear understanding of the basic ideas in mathematics, construction of proofs, problem solving, and scientific exposition.

Students should visit prospective programs to obtain more information. Often the program will arrange a visit and will contribute to travel expenses. Talking with students currently enrolled in the program is very useful. Students should investigate the library, the computing facilities, the office space, and the study space.

One of the main themes in this report is how important the learning environment is for student success. Students should seek programs with a positive learning environment, that is, programs that actively provide advice and support for course work, qualifying examinations, research, and the thesis. The learning environment can make the difference between failure and success in graduate school.

Most doctoral students in the mathematical sciences can obtain full financial support in the form of fellowships, teaching assistantships, or research assistantships. It is important that prospective students, before enrolling and accepting an offer, know about the work load for teaching and research assistants and the availability of other support. Generally, spending more than a total of 20 hours a week on work other than studying, such as teaching more than one course or meeting students for more than four class hours a week, impedes satisfactory progress toward a doctoral degree.

Prospective graduate students should know the answers to the following questions before deciding to enter a program.

- What is the mission of the program; that is, in what areas (subdisciplines, applied/interdisciplinary work, industrial problems, preparation for university teaching, and so on) does it specialize and what are its goals in those areas? Are the areas of specialization consistent with the areas in which you would like to specialize?
- At what level does the program begin?
- What is the completion rate? (Students should be wary of enrolling in a program with a low completion rate.) What is the average length of time to a doctorate? What is the placement record for new PhD graduates?
- Does the program have a positive (supportive) learning environment? Are advisors available? Will course work provide a sufficiently broad background in the mathematical sciences? Is support in studying for qualifying examinations available from the department or from groups of students? Is clear information on the qualifying examinations and on the research period available from the department?
- What type of financial support is available? What teaching work or other work is required to obtain that support? Will that work realistically take 20 hours per week or less?

Care in the selection of a graduate school will lead to a more successful doctoral experience.

APPENDIX C

PROFESSIONAL MASTER'S DEGREE PROGRAMS IN THE MATHEMATICALSCIENCES

There is a great need within government, business, and industry for well-trained professional mathematicians educated beyond the level of a bachelor's degree, but below that of a doctorate. Making available a professionally recognized stopping point short of the PhD, such as the *Diplom* in Germany and the *diplôme* in France, could make the mathematical sciences more attractive to students.

Currently, the master's degree in the United States is a valued degree in various areas of statistics, operations research, scientific computing, and elementary-and secondary-level mathematics education. It is important for positions in business, industry, government, and education that fully utilize the holder's mathematical talent and education. It does not, however, have the same status in pure and applied mathematics. In these areas, it is often viewed as being a poor second choice to a PhD rather than an important degree in its own right. In these areas, candidates who complete the doctoral program core courses but fail to pass the first qualifying examination may opt for a master's degree.

Doctoral programs would benefit from being complemented by a successful master's degree program. Success for a master's degree program is created by the same things that create success for doctoral programs—a focused and realistic mission, a positive learning environment, and professional development for the future careers of the students. A successful master's degree program could attract domestic students who do not yet have the confidence to attempt doctoral studies. Some students who finish master's degrees would seek to further their studies in a doctoral program. Some PhD students in engineering and social sciences who obtain master's degrees in mathematics or statistics to raise their status would be attracted to continue studies in the mathematical sciences. The doctoral program would benefit by having attracted students who would otherwise not have continued their studies or who would have chosen to continue in another discipline. The key to all of this working is that the master's degree must be perceived as having intrinsic value itself and not as being a second choice.