The Growth of the Professional Master's in Mathematics

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"Mathematics has an age-old mission in unifying the sciences and technology."
—Avner Friedman, 1993

In terms of student enrollment, American mathematics is in crisis. Although secondary school students increasingly express an interest in mathematics, the number of mathematics majors is declining. Students choose, instead, majors that lead more directly to jobs in today's technological workplace [AMS]. While industry needs mathematically trained people, it hires few mathematicians—a consequence of our discipline's century-long disengagement from industrial work.

But this bad news has been allayed in the past decade by the flourishing of a professional master's degree in mathematics, one that promises new careers for the serious student of mathematics. Skeptics argue that such programs are devoid of serious mathematical content, attract weaker students, take resources and students from the traditional Ph.D. program, and force departments to offer fewer courses in traditional mathematical areas. Practitioners, however, point to many benefits, both for the providers and for the students, that disarm the objections of the skeptics. Jay Walton, whose mathematics department at Texas A&M began offering the professional master's options in 1994, reports an increased visibility for the department both inside and outside the university, an increase in collaborations with other departments, an increase in graduate mathematics course enrollments by nonmathematics graduate students, and an increase in the proportion of university resources targeted for the mathematics graduate program. Moreover, none of these benefits have come at the expense of the Ph.D. program, which, at Texas A&M, has steadily increased in size and quality over the six years the professional master's options have been offered [JW].

In what follows we will sketch the growth of the professional master's degree (the first new degree since the MBA at Harvard in 1908), what niche it fills, how it is implemented at several institutions, and its potential benefits to the mathematics community as a whole.

The Origins

In 1995 the Committee on Science, Engineering, and Public Policy (COSEPUP) of the National Academy of Sciences suggested that graduate schools of arts and sciences might consider a "different" kind of graduate degree, less oriented toward research and requiring less time to obtain [CU]. The difficult labor markets faced by many new Ph.D.'s and postdocs and the growing number of part-time and adjunct faculty contributed to the view that the Ph.D. degree might not be the best terminal degree for many science- or mathematics-trained professionals. The COSEPUP Report was a long-delayed acknowledgment that graduate education in the sciences had become severely

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decoupled both from the career needs of students and from the supply needs of an ever more technically based national economy [MG].

Even before the National Academies had broached the topic, there were stirrings in the mathematics community. At conference after conference, beginning in the late 1980s, and in journals like this one, talks were given and articles appeared with titles like: "Preparing for a job outside academia" [Ben94], "Preparing M.S. and Ph.D. students for nonacademic careers" [BLTSLD93], "The mathematical training of the nonacademic mathematician" [Boy75], "Graduate education in transition" [CBMS92], and so on. At the helm of the nascent movement was SIAM, the Society for Industrial and Applied Mathematics, which recognized early that not only were there jobs to be had and interesting careers to be made by mathematicians in business and industry but that some of the more interesting problems in mathematics could come from such settings.

For most of the sciences, reform was thought about in terms of doctoral education, for what else is graduate education in the sciences but doctoral education?

Reinventing the Master's Degree

All the while, the "silent success" (see Table 1) of the terminal (professional) master's degree in fields other than science and mathematics was pointing in another direction. Beginning in the late 1980s, an increasing number and proportion of M.S. degrees were being awarded in professional fields, with M.S. degrees in arts and sciences in decline.

In their 1993 study of master's education in the U.S., commissioned by the Council of Graduate Schools and supported by the Pew Trust, Conrad et al. posited an important distinction between master's degrees: the predoctoral (or, when terminal, the failed Ph.D.) versus the self-contained professional certification [CHM93, p. xiv]. As they describe

Table 1. Number of master's degrees conferred by fields of study

Year	Professional*	Arts and Sciences**	Mathematics	Total
1996–97	326,895	14,219	3,783	419,401
1995–96	317,559	14,229	4,031	406,301
1994–95	310,514	13,312	4,181	397,629
1993–94	301,454	13,164	4,100	387,070
1992–93	288,358	12,365	4,067	369,585
1991–92	272,004	12,403	4,011	352,838
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1990–91	259,724	13,369	3,615	328,645
1989–90	253,544	13,700	3,676	322,465
1988–89	243,268	13,929	3,447	309,770
1986–87	224,942	14,101	3,319	289,341
1984–85	218,285	14,586	2,831	280,421

Source: U.S. Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System, "Completions" survey and "Consolidated" survey, for the quoted academic year.

*Professional includes Education, Health Professions, Business Administration, Engineering, Psychology, Computer Science, Public Administration, Library Sciences, and Law.

**Arts and Sciences includes Physical Sciences, Agricultural Sciences, and Biological Sciences.

***Change in source definitions of fields of study.

it, this professional degree is "...an important means for enriching the knowledge base and skills of pre-professionals in an information-centered society." Furthermore, "...people with master's constitute the professionals upon which business, industry, education, government, and the nation's health care systems are increasingly coming to depend for expertise and leadership" [CHM93 p. xiv].

"What kind of professional master's degrees might we invent for science?" asked the authors of *Rethinking Science As a Career* [TCA95], and how, once these degrees were in place, could they be marketed to faculty, students, and to the employing and subsidy-paying public? If one looks to the master's degree more generally, one finds that instead of training producers of scholarship—the traditional purpose of graduate education—master's educators aim to produce people who are able to use the products of scholarship in their work and who are familiar with the practical aspects of emerging problem areas. So the general outlines of a professional science or mathematics master's degree were available to the community in the mid-1990s. The next task was to begin the process of persuasion and develop the momentum necessary to launch the new degree.

The Role of AMS, MER, and SIAM

There is no question that the mathematics community itself played a leading role in expanding the professional master's degree from a narrow band of programs in fields such as actuarial science and teaching to a wider range of subject specialties and applications. First, there was industrial and applied mathematics. In the 1980s Avner Friedman, president of the Society of Industrial and Applied Mathematics (SIAM) during 1993–1994, launched the Institute for Mathematics and its Applications (IMA) at the University of Minnesota, followed (in 1993) by Friedman's and John Lavery's booklet, *How to Start an Industrial Mathematics Program in the University* [FrLa]. SIAM's next influential publication, *Mathematics in Industry* (1995) [MI95], based on interviews with 500 mathematicians in industry and their managers, documented the need for graduates specifically trained in a combination of mathematics, applications, and computation. By May 1998 SIAM had secured National Science Foundation (NSF) funding for a series of regional workshops both to build bridges between industry and academia and to encourage the founding of professional master's degree programs.[1]

Typically, mathematicians from industry and their faculty counterparts were invited to talk about (1) the latest applications of mathematics, (2) the benefit to faculty and students from interactions with industry, and (3) the design and implementation of new programs [Online resource: SIAM98]. The idea behind the workshop series, according to one of its organizers, was that (1) and (2) would lead naturally to (3). The goal was to have participants from other universities learn about these efforts and, if possible, implement their own [Online resource: DAVIS]. To further propagate the idea of the professional master's, a set of "Guidelines for the Professional Master's in Mathematics", prepared by SIAM, is scheduled provisionally for publication in July 2001. The "Guidelines" will recommend a core curriculum; course work or training in presentation and writing skills; and internships in business, government, or industry. Appended to the brochure as a kind of existence proof will be descriptions of several professional master's programs from a variety of institutions [SIAMGuidelines01].

Meanwhile, furthering a different but complementary agenda, the American Mathematical Society (AMS) and the Mathematicians and Education Reform Forum (MER) organized two national workshops, the first at New York University on November 5–7, 1998, and the second at Arizona State University on November 4–6, 1999. The organizers' intention was to stimulate departments of mathematics to think creatively about their mission in graduate education and as part of that to consider the range of professional master's that were available to them. Twenty-seven departments were represented at the NYU workshop and thirty-three departments were represented at the ASU workshop. To further support departments, AMS and MER are producing a directory of professional master's programs, based on their survey of 426 master's- and Ph.D.-granting mathematics departments, which both interested faculty and prospective students will be able to access online [Online resource: MER].

While AMS, MER, and SIAM deserve credit for encouraging the establishment of the professional master's degree by way of publications and numerous workshops, two contemporaneous developments have given the professional master's a further boost: first, the emergence in the 1990s of a Professional Master's in Financial Mathematics in some of the nation's most prestigious institutions; second, the commitment on the part of two national foundations, beginning in 1997, to support the establishment of new professional science master's programs in which mathematics would be an integral part.

With the stock market gaining in visibility in the early 1990s and the increasing mathematical complexity of financial instruments, a sizeable number of physicists and mathematicians began finding their way to Wall Street. This bloom in

[1] *SIAM Workshops: Northeast, May 18–20, 1998, Worcester Polytechnic; Midwest, October 2–3, 1998, Univ. of Illinois at Chicago; West, June 16–19, 1999, The Claremont Colleges; Southeast, October 10–12, 1999, North Carolina State Univ.; Northwest, October 12–14, 2000, Washington State; Southwest, April 2001, Houston.*

Online Resources

[SIAM98]	`http://www.siam.org/meetings/archives/index.htm#m11`
[DAVIS]	`http://www.wpi.edu/~heinrich/MII.html`
[MER]	http://www.math.uic.edu/MER/masters.html
[KGI]	`http://www.kgi.edu/`
[SLOAN]	`http://www.sloan.org/` (Sloan Science Master's Initiative)
[SCI]	`http://www.sciencemasters.com/`
[Ga]	`http://www.qcf.gatech.edu/`
[WISC]	`http://www.wisc.edu/computationalsciences/`
[ARIZ]	`http://cos.arizona.edu/sloan/`
[MSIM]	`http://www.math.msu.edu/`

opportunities certainly fueled the establishment of master's-level graduate programs in financial mathematics. The oldest among them is Computational Finance at Carnegie Mellon University (1992), followed soon after by Financial Mathematics at University of Chicago, Mathematics with Specialization in the Mathematics of Finance at Columbia University, and Mathematics in Finance at New York University.

Meanwhile, the NSF-funded workshops stimulated the expansion of master's programs in applied and industrial mathematics. Examples of programs established during this period are at the University of Massachusetts, Amherst (established in 1989) and Carnegie Mellon (established in 1992); the University of Illinois, Urbana-Champaign; Clemson; Texas A&M; and Virginia Tech. Of these new degree programs, only Texas A&M employs the term "professional" as a descriptor. But because of the participation of industrial contacts and the effort to attract the nonpredoctoral student, the programs are de facto professional.

The Keck and Sloan Foundations' Initiatives

In 1997 both the William M. Keck and Alfred P. Sloan Foundations, independently, began to explore the possibility of launching new professional science master's degrees. Keck was approached by Henry Riggs, the outgoing president of Harvey Mudd, the science and engineering college in the Claremont Colleges group. Riggs wanted to build an all-new, master's-only graduate school to supply California's biotech industry with professionals skilled in the life sciences, mathematics, and engineering, but who were also knowledgeable about intellectual property rights, finance, and business management, particularly as applied to biotechnology. The resulting institution, Keck Graduate Institute, which enrolled its first class of twenty-eight students in August 2000, recruits graduates in mathematics along with graduates in the life sciences, engineering, physics, and chemistry [Online resource: KGI].

The contribution of the Sloan Foundation was to embed mathematics in a broader concept of the "science master's" and to provide start-up funding for program development [Online resource: SLOAN]. Unlike the Keck Graduate Institute, with its dedicated biotechnology program, Sloan was willing to entertain any program of study—ideally in an emerging discipline or combination of fields—for which a faculty group could document that there were employment possibilities for graduates at the master's level. As of this writing, Sloan has funded twenty-four degree "tracks" in seventeen Ph.D.-granting institutions, of which ten tracks (in six different institutions) are in mathematics. With a substantial degree of local initiative and local control, the mathematics tracks funded by Sloan are not of a single type, although all require business/industry interaction [Online resource: SCI].

For example, in Michigan State's Professional Master's Degree Program in Industrial Mathematics, students are expected to complete a ten-module business certificate program; in Arizona's Mathematical Sciences Master's program, students take two semester-long courses, one in basics for business, one in the legal environment of business. In contrast, students enrolled in the Quantitative and Computational Finance track at Georgia Tech take all their courses in financial instrument development and usage, investment, and risk analysis, with an emphasis on the construction, implementation, and testing of models used in these areas of finance [Online resource: Ga]. Unlike many of the other professional mathematics degree programs, which are creating new configurations largely of existing mathematics and computational science courses, Georgia Tech's, with ten new courses, is building a new discipline. Director Robert Kertz says students in the program will be able to select different emphases and specializations. Currently, eighteen are enrolled in the program's first year.

Two of the authors (MacCluer and Svetic) direct an Industrial Mathematics Professional Master's program sponsored by Sloan at Michigan State University. Fifteen students are currently enrolled in its second year of operation. The degree requirements are four courses in applied mathematics, four courses in engineering or economics, two courses in statistics, a fall term survey of industrial mathematics (taught from MacCluer's text [CRM]), and a spring term project course with local industry. The process of discovering the underlying mathematical character of any interesting problem is a critical part of the training for the students. The industrial projects are managed by faculty from various departments and coordinated by MacCluer and Svetic. Ralph Svetic has brought verisimilitude to these projects from his fifteen years of industrial experience. Each project engages students in solving a single real-world problem provided by local industry (see below). The problems are solicited by Svetic and MacCluer, who mold them into semester-long projects solvable by two- or three-person teams of master's students. Undergraduates serve as assistants to the graduate student teams, exposing the undergraduates to industrial mathematics and the graduate students to management responsibility. At the end of the semester the teams generate a formal report and present their findings both to fellow students and on site to their industry liaisons, a presentation to which a large number of people from the client organization are invited. The on-site event increases the visibility of the Michigan State program and exhibits the quality of the students being produced. The students are astonished by how many people are actually interested in what they have done.

In 1999 Sloan funded a professional master's in mathematics program at Worcester Polytechnic Institute (WPI). It features two tracks, one in financial mathematics, coordinated by Domokos Vermes, and the second in industrial mathematics, coordinated by Bogdan Vernescu. Students in both tracks, however, are able to participate in industrial projects and internships facilitated by the established connections of WPI's Center of Industrial Mathematics and Statistics. To give students a competitive advantage in careers that require the combination of sophisticated quantitative skills and a thorough understanding of the underlying industrial problem, the industrial mathematics program features coordinated modules of mathematics and engineering/science courses in areas like dynamics and control, materials design, fluid dynamics, biomedical engineering, machine learning, cryptography, etc. The anticipated job opportunities for graduates in financial mathematics are in the money management and insurance firms in the Boston-Hartford financial corridor near WPI. Therefore, the main thrust of the financial mathematics degree program is to provide the skills and knowledge needed in asset-liability management, portfolio selection, risk control, and financial product development.

Another way that mathematics is being reconfigured in a professional master's degree program is demonstrated by the University of Wisconsin's Sloan-funded Professional Master's Degree in Computational Sciences, chaired by Gregory Moses. The degree is intended to prepare students with bachelor's degrees in science and engineering for careers in advanced computing applications such as parallel computing, grid computing, and visualization/animation [Online resource: WISC]. Meanwhile, Arizona's master of mathematical sciences features interdisciplinarity and the possibility of tailoring programs to individual students' interests and needs. For example, among the first three enrollees at Arizona (2000–01) are a full-time student doing his M.S. thesis in bioinformatics; a full-time student working on image analysis after an internship at Raytheon; and a part-time student, fully employed at Raytheon, working on signal analysis [Online resource: ARIZ].

The newest family of Sloan-funded programs at the University of Pittsburgh is remarkable because of its four separate tracks within the Department of Mathematics: Mathematical Modeling of Complex Systems (coordinated by Carson Chow), Industrial Mathematics (coordinated by Xinfu Chen), Scientific Computing (coordinated by William Layton), and Analytical and Computational Methods in Finance and Risk (coordinated by John Chadam). Yet all four are designed around a core of courses required of all students: Methods of Mathematical Analysis, Scientific Computing Techniques, Statistics and Stochastic Methods, and Dynamical Systems. Upon completion of the core, students enroll in "focus courses" in each of the four tracks and, depending on individual interest, a group of related courses offered by other departments, including engineering.

Incorporating Industrial Participation

How does a program in industrial mathematics actually operate? What kinds of interactions with industry are feasible in practice? We discuss some examples from the program that we supervise in the hope that our experience may be useful to others who plan to create similar programs.

Our Professional Master's in Industrial Mathematics is, as we have said, built around real-world problems solicited from and then delivered back to industrial clients. The staff begins a year in advance to solicit projects from local industry. This involves "cold calling", chasing down any leads, persistently calling back, and keeping a careful diary of all contacts. Whoever makes the first call explains the program and asks the contact to "help us better educate our students." In any one year, forty companies are contacted, with an eventual yield of 5–8 projects. Our guiding principle is to take on any "interesting" problem, on the presumption that behind every interesting problem lurks interesting mathematics. What follows are descriptions of the kinds of problems provided by local industry and government to the student teams. The problems can be examined in more detail at [Online resource: MSIM].

B. F. Goodrich Avionics asked for help in correcting temperature-induced errors in a solid-state roll sensor. Careful graphing of the experimental errors revealed a hysteresis pattern—the errors took different paths during cooling of the sensor and heating of the sensor. This hysteresis turned out to be merely the thermal delay as heat diffused in and out of the sensor case, easily corrected by inserting a software block simulating heat diffusion.

In the current year McCleer Power Inc., a premier electric motor design firm, has provided three problems. One of these involves the most expensive and failure-prone components in future 42-volt automobile power inverters (which transform DC to three-phase AC), namely, the electrolytic capacitors that are hung across the DC bus to smooth out the square-wave current trains drawn by the pulse-width modulating inverters. The students' job is to search for an alternate pulse-width modulation pattern that will reduce the required number of electrolytics. This may involve a huge search via a genetic algorithm. Another team will determine the optimum size ratio of the electric motor and the gasoline engine in hybrid vehicles. A third team will optimize wind generator design.

Another student team helped the Air Toxics Division of the Michigan Department of Environmental Quality decide if it would be advantageous to switch from 6-day sampling to 12-day sampling for noncriteria pollutants, using the savings to invest in additional testing sites. The students found 12-day sampling too dangerous because important events will be missed. They also suggested an ingenious method for accounting for "no-detects" (readings below the instrument's threshold).

We outreach to our own university researchers. In the current year a student team will model the outbreak of a certain grape pest along the shore of Lake Michigan using degree-day data. Last year a team analyzed the forensic use of fiber evidence by applying small-world network theory (of "Six Degrees of Separation" fame).

Neogen, a Lansing firm that manufactures test kits for detecting pathogens, has proposed four interesting problems: One proposal is to model the dispersion of E. Coli via groundwater, where E. Coli may adhere to clay particles, bloom, and thereby become a new point-source. Other problems concern sampling strategies for detecting pathogens or the presence of genetically modified grains.

Artificial wetlands are being designed and built within suburban neighborhoods to retain and absorb storm water runoff. One student team studied Ingham County's demonstration wetland and derived its water-level response to an arbitrary rain event (via convolution with its impulse response, derived from the generalized derivative of its response to a "unit rain event").

Another team of students constructed for Delta Dental of Michigan a clustering of states into similar fee-for-service groups. For some reason, the students did not choose the more interesting problem of predicting monthly claims given the contracts outstanding.

Instrumented Sensor Technologies manufactures recording sensors that are embedded in solid rocket fuel in order to record the thermal cycling that induces microcracks. The company would like the students to model the propagation of cracking given temperature history for use in determining the remaining shelf life of the propellant.

Our cold calling has been unexpectedly successful—we are embarrassed by a surplus of projects for which we are unable to constitute teams. We are presently experimenting with a process by which we "farm out" surplus projects to other institutions with similar master's programs.

It is made clear to the client from the outset that these are student projects, with faculty playing only a supervisory role. Indeed, the students take away from these exercises invaluable lessons, the equivalent of experience in industry. At first they are wary of taking on an industrial problem that they may not be able to solve. They soon learn, however, that industrial problems are never "solved" in the way end-of-chapter problems are solved; rather that only pieces of the problem can be resolved given the time allotted. Nevertheless, these solutions have real value to the firm, because they permit the product development to continue.

Conclusions

Current professional master's programs appear to be doing well, in that they enjoy selective faculty/administrators' support and the willingness of students to enroll. The true test of their utility (and hence their viability) comes when their graduates go on the job market with their new degrees in hand. There is a clear tendency among hiring managers to "hire a degree". What once was descriptive (such as "hire me the kind of person who can solve a technical problem") has become prescriptive ("hire me an engineer"). It will take significant marketing of the new degree to change corporate culture. On the one hand, certain business and industry representatives have reported that "the master's is our missing degree" and that the traditional MBA is not as relevant in a high-tech economy as it once was. On the other hand, there are few professional master's graduates in management to smooth the way for others. A critical test of the "promise" being made to students will be their career trajectories. The first graduates will need to cut steps in stone as they sell themselves and their degrees. Networking and tracking of graduates of the programs are therefore essential.

A second potential problem might be that, as outside funding ends, professional master's degree programs will be reabsorbed into existing departments and will lose their special characteristics. Or, should the programs succeed, they might be taken over by colleges of business and/or engineering. Avner Friedman talks about a "total and enduring commitment" by administrators for such new programs. The same could be said for the faculty. Faculty are enthusiastic, but few can afford to make the professional master's their first priority.

A third potential problem is quality control. Absent a thesis, national boards, or state bar exams, how will the wide variety of professional master's programs (many crossing traditional disciplinary boundaries) be accredited? The engineering accreditation organization ABET 2000 is facing the same dilemma. Although SIAM's guidelines may not be intended to set standards, this may be their practical effect. To some extent, mathematics has an advantage over the sciences—compared to "human-computer interaction" or "environmental risk management", the mathematics that master's candidates need to know is fairly well laid out.

Despite uncertainties, the mid-term outlook for the professional mathematics master's is very promising. Not every company contacted by MSU's program provides a problem for the students to solve. But all are pleased to be asked, and all tell the program directors that the students being trained are precisely the kind of "knowledge workers" the company needs.

Those involved in the professional master's movement believe that supplying the nonacademic workplace with mathematics (and science) professionals will have four benefits: (1) an increase in the number of students willing to major in mathematics; (2) an increase in appreciation for mathematics training among managers and policy-makers; (3) an increase in funding for mathematics research; and, as a result of all of these, (4) an increase in the demand for faculty as the new professional programs, now having total annual enrollments of only a few hundred, increase five- or ten-fold. But first, academic mathematicians will have to become convinced that it is in their interest to incorporate real-world problems in their teaching and to encourage workplace-oriented students to pursue the master's degree in mathematics.

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[AMS] Undergraduate enrollments: Between 1985 and 1995, enrollments in calculus dropped 15%, from 637,000 to 539,000; in advanced mathematics, from 138,000 to 96,000, a decrease of 30% (at 30 students per section, that's a loss of 1,400 sections per year; at 4 courses per year, 350 fewer mathematics faculty are needed). Mathematics majors: Between 1975 and 1995 a decrease from 18,883 to 12,456, a decrease of 33%. Graduate course enrollments: Between 1992 and 1997, 18.5% decrease (overall) and 28% in Group I Public universities…even higher decreases in the number of first-year graduate students. Data from "Mathematical landscape in the U.S. at the end of the century", unpublished presentation by John Ewing, executive director of the American Mathematical Society, at September 30–October 2, 1999, Conference on Summer Undergraduate Mathematics Research Programs, conveyed in summary form by e-mail to the authors.

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