A Concept Paper for an Interdisciplinary Ph.D. Program

in

Mathematical Modeling and Scientific Computing

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ABSTRACT

We propose a Ph.D. program in Mathematical Modeling and Scientific Computing that will provide graduates with a solid foundation in the development and application of mathematical models of real-world problems. It will be a cohesive, interdisciplinary program that will be complementary and, even more important, synergistic to other RIT programs. Such a Ph.D. program will enrich RIT's learning environment and will prepare scientists to deal with and adapt to rapidly changing environments. A Ph.D. in Mathematical Modeling and Scientific Computing will fit the RIT mission well and will help present a consistent image or RIT "brand". Graduates of this program will become vital members of interdisciplinary teams that will model and simulate complex systems and solve real-world problems from a wide range of fields. The United States Bureau of Labor Statistics forecasts optimistic employment prospects for those with advanced training in mathematical modeling and scientific computing: *"Master's degree and Ph.D. holders with a strong background in mathematics and related disciplines, such as engineering and computer science, and who apply mathematical theory to real-world problems will have the best job prospects in related occupations."* Graduates of the proposed Ph.D. program in Mathematical Modeling and Scientific Computing will be highly employable in all sectors, such as defense laboratories, government agencies, corporate research and development, and, when desired, follow traditional academic careers.

PROGRAM DESCRIPTION

1. Overview and Justification

Modeling and scientific computing are essential components of research in all modern scientific and technical disciplines. Mathematical modeling has become a critical tool of research and is naturally cross-disciplinary, spanning applied mathematics, scientific computing, the physical and life sciences. Every mathematical modeling enterprise has four aspects: the content of the application field, the mathematical formulation and analysis, the analytical and computational machinery and methods, and the interpretation and analysis of the results. Successful modeling enterprises succeed because those who undertake them understand that applied mathematics is *crucial* to the enterprise. Unsuccessful modeling enterprises fail because the mathematics is not done properly or because the output of the mathematics is misunderstood. Scientists, engineers, social scientists, business professionals, physicians, and other specialists are experts in the content of their fields: in physics, chemical engineering, psychology, or finance. The practice of devising, analyzing, and computing solutions of novel systems of equations that arise in these fields is a specialty in itself; it is the specialty of the applied and computational mathematician. Because this specialty is essential to the practice of sciences and engineering in the mature computer age, RIT, a full-fledged Institute of Technology, should offer a Ph.D. program in applied mathematics with focus on modeling and scientific computing.

The proposed program integrates applied mathematics with scientific computing and is interdisciplinary in nature, encompassing the physical, life, medical, computational, social, and management sciences. Graduates of this program will become vital members of interdisciplinary teams that will model complex systems and solve real-world problems from a wide range of fields. Above all, the proposed program will train researchers who can communicate across the fields of sciences and mathematics and will complement existing and developing strengths at RIT, including imaging science, astrophysical sciences, computing, biomedical engineering, and sustainability. This program aims to produce graduates who will have abundant opportunities for employment throughout the private and public sectors. As conceived the RIT program in Mathematical Modeling and Scientific Computing will meet the needs of society in pragmatic ways and will educate and empower scientists to develop modeling, computational, and problem-solving skills with substantial breadth and depth impacting a wide range of fields. The 2008 Society for Industrial and Applied Mathematics (SIAM) Report on Mathematics in Industry [1] surveyed mathematicians and managers in companies, government organizations, and national laboratories. Among its many findings was that managers considered modeling and computation to be the mathematical functions of greatest value in successful industrial applications.

> *"Mathematicians are valued [in industry] because they can see and understand the inner nature of a problem; determine which features matter and which do not; and develop a mathematical representation that conveys the essence of the problem that can be solved numerically."*

Because we aim to address an important area of science where little formal training currently is offered, we expect that the unique integrative skills our program will cultivate will be highly valued. The program will prepare students to fill industry, government, and business needs in developing, implementing, and using models. It also will prepare them for postdoctoral work, for academic opportunities in various applied fields, and to work in leading national research laboratories.

2. Summary of Curriculum

This program is not a mathematics program for the sake of mathematics nor it is synonymous with the existing Ph.D. program in Computing and Information Sciences, but rather it is a distinct program firmly rooted in mathematics with emphasis on modeling and scientific computing. While there are numerous Applied Math graduate programs, including many Ph.D. programs across the Northeast and the United States as a whole, our program's focus on broad problem-solving skills involving modeling and scientific computing most closely mirrors the Center for Scientific Computation and Mathematical Modeling at the University of Maryland, which focuses on interdisciplinary research between mathematicians and researchers in physical science, biological science, and engineering. This is a niche that has only begun to be explored across the academic community, and RIT is well-positioned to enter this field during its formative period. While some other schools are establishing similar programs, e.g., the University of Ontario Institute of Technology Ph.D. program in Modeling and Computational Science, several others with similar names are much more centered on engineering applications, whereas we envision our program to have a broader underlying basis of research fields (examples include the Ph.D. Program in Computational Modeling and Simulation at the University of Pittsburgh, Ph.D. programs in Modeling and Simulation at Old Dominion University, the University of Central Florida, and the University of Alabama in Huntsville, and the Ph.D. program in Computational Analysis and Modeling at Louisiana Tech). Because of the interdisciplinary nature of the program, students will be recruited from chemistry, biology, psychology, materials science, imaging science, computer science, engineering, economics and other social and physical sciences disciplines.

Students who will be admitted to the program will complete core courses in modeling and of scientific computing to gain understanding how to construct and analyze mathematical models, how to develop analytical and numerical techniques to solve problems in various disciplines, and how to implement mathematical models using computers. These core courses will be housed in the School of Mathematical Sciences and will emphasize the mathematical foundations of both subjects. The modeling course will be more than an applied mathematics course: it will focus on the philosophy behind modeling, on what types of model formulations can be used, and on what trade-offs must be made in constructing a model, so that students will learn how to develop and select models appropriate for solving specific problems. The scientific computation course will combine applied numerical analysis with a focus on practical aspects of computing, including choosing numerical techniques, computing architectures, and representations of problems and solutions that are appropriate to various applications. After passing the qualifying exams on the core requirements, students will craft a tailored program of study to map out, in a unified manner, an application-specific curriculum culminating in a Ph.D. dissertation. The required concentration in an application field will result in students taking classes in other programs and colleges; this makes the Mathematical Modeling and Scientific Computing Ph.D. program an interdisciplinary endeavor that requires strong linkages from all colleges across RIT. Altogether, this training will allow students from diverse areas to integrate their backgrounds with the skills necessary to tackle complicated modeling problems in a broad range of disciplines.

FIT WITH RIT MISSION AND STRATEGY

The doctoral program in Mathematical Modeling and Scientific Computing will fit well with RIT's mission and brand image. The objectives of our program are tightly aligned with the RIT Strategic Plan 2005-2015:

- *Preparing students for innovative careers.* Our proposed program is in an overlooked area at the intersection of mathematics, sciences, and engineering. Students will be equipped with skills to work between disciplines, which in turn will facilitate novel research contributions.
- *Providing career-oriented educational programs.* This program will not only attract students who aspire to academic careers, but it also will meet the growing needs of industry for modeling by training students to thrive in corporate environments and in national labs.
- *Engaging students through collaborative experiences.* Modeling requires its practitioners to understand high-level mathematics, programming languages and algorithms, computing architectures, and real-world data and to master the interpretation of results. Integrating these components is accomplished most effectively through collaboration. Moreover, our program will be interdisciplinary by nature and will

value contributions from a broad range of disciplines. Thus, students will be expected to work with others who have complementary knowledge and skills.

RIT has always had a practical bent to its endeavors by offering many undergraduate and graduate programs that have excelled in providing industry with strong technical graduates. However, jobs in industry and government are becoming increasingly challenging and demand a higher and more intense level of technical sophistication, skill and innovation. Establishing a Ph.D. program in Mathematical Modeling and Scientific Computing will infuse the entire sciences, technology, engineering, and social sciences community at RIT, and it will prepare scientists capable of dealing with and adapting to rapidly changing environments. It will attract many students and can, therefore, be the focal point of such disciplines and become a resource for and good partners with all existing and future Ph.D. programs. Such a program will fit the RIT mission well and will help present a consistent image or RIT "brand."

SYNERGY WITH OTHER PROGRAMS

A Ph.D. program in Mathematical Modeling and Scientific Computing will complement the already high-quality undergraduate and graduate programs offered by the College of Science and the other colleges of RIT in providing and discovering new knowledge. A new Ph.D. program would create an infusion of new research projects and research teams from across many fields. Because mathematics is so central to many other disciplines, the proposed Ph.D. program will allow faculty from a large number of programs to participate in graduate research. A Ph.D. thesis committee will consist of faculty from various disciplines, and a Ph.D. student will be taking courses from several other programs.

RIT can be in a better position to make innovative advances in the STEM disciplines by having Ph.D. doctoral advisors, Ph.D. candidates, and post-doctoral researchers working together. It is now generally accepted that theory, experiment, and computation comprise the three pillars of modern science. Applied mathematicians are routinely called upon by experimentalists to work out the theories and computations that explain experimental data. There are numerous faculty and student researchers all across RIT, who may not have the mathematical or numerical training needed to fully analyze a problem, perform experiments and build devices. Researchers from RIT colleges and departments, such as imaging science, physics, mechanical engineering, electrical engineering, chemical engineering, psychology, economics, and others have, in the past, come to the applied mathematics faculty seeking collaboration and assistance with research questions. A Ph.D. program in Mathematical Modeling and Scientific Computing would further stimulate and deepen such cross-departmental collaborations, both among students and faculty.

The required concentration in an application field will truly make the Mathematical Modeling and Scientific Computing Ph.D. program an interdisciplinary endeavor and will require strong linkages will all colleges across RIT.

ADMINISTRATIVE STRUCTURE

The Ph.D. in Mathematical Modeling and Scientific Computing program will be housed within the School of Mathematical Sciences (SMS) in the College of Science. The main governance will be a Program Director who will be selected from the faculty engaged in the program. According to the September 28, 2008 Memorandum (https://www.rit.edu/~w-drupal/sites/rit.edu.provost/files/faculty_and_director_hiring_expectations.pdf), the Provost in consultation with the dean makes the final selection for the directorship of the Ph.D. program. The Ph.D. program director will oversee the budget of the program, student recruitment, and delivery of the curriculum; will advocate for the program; will monitor students' progress; will allocate teaching responsibilities; and will work with the department heads and school heads of the constituent faculty to provide feedback as to the contributions of their faculty to the program.

ENROLLMENT MANAGEMENT EXPECTATIONS AND SUSTAINMENT

We believe that many of the initial conditions necessary to make the proposed Ph.D. program successful already exist. There are currently 15 faculty members, all of whom have been involved in drafting this concept paper, who are actively involved in research and are interested in becoming graduate faculty of this program. These faculty members are currently part of 19 separate actively funded grants (from both federal agencies and industry sources) that sum to over $4.1 million. In addition to this core of faculty, there will be 5 new, research-focused hires that are taking place this year due to retirements. There also will be participation of program faculty from outside the School of Mathematical Sciences who will be advising and supporting Ph.D. students on research grants, will be teaching courses in the program, when appropriate, and will be serving on thesis/dissertation committees.

We estimate that we can take on approximately 16 to 20 students total or about 4 to 5 per year. Between the core faculty, the new hires that are taking place this year, and the program faculty from outside the School of Mathematical Sciences, we are well suited to maintain an enrollment of that size. Because of the interdisciplinary nature of the program, students will be recruited from mathematics and applied mathematics programs as well as physics, computer science, engineering, chemistry, and other sciences. This flexibility should enable the continued recruitment of quality students.

Because virtually every field uses mathematical models and computer simulations, students from the Mathematical Modeling and Scientific Computing program will be well positioned to get jobs in research and industry. Furthermore, there is external funding available for mathematical modeling and scientific computing to support both research and the training of students, including government agencies as well as private foundations and corporations. Current sources of funding include NSF, NASA, NGA, DOE, Bausch & Lomb, , AFOSR and others. Potential new sources include DOD, DARPA, ONR, NIH, as well as national and defense labs.

FACULTY AND TEACHING RESOURCES

The number of faculty in the applied and computational sciences at RIT has expanded rapidly over the last few years, and RIT has critical mass and expertise in a range of modeling and computation areas. RIT faculty with a Ph.D. in applied and computational mathematics and related disciplines will be eligible, regardless of department or college, to be members of the Mathematical Modeling and Scientific Computing graduate faculty. Each graduate faculty member in the Ph.D. program will be expected to supervise and mentor one or two Ph.D. students, write grant proposals, teach one course per term, and conduct research.

After completing the core requirements of the program, students will be encouraged to take classes in other disciplines to craft a tailored program of study that will map out an application-specific curriculum culminating in a Ph.D. dissertation. It is anticipated that faculty from other disciplines will advise Mathematical Modeling and Scientific Computing Ph.D. students. Faculty from Mathematical Sciences, Physics, Imaging Sciences, Psychology, Economics, Public Policy, Computer Science, and from many of the engineering programs have been collaborating in the areas that involve modeling and scientific computing. Indeed the program title articulates the expectation that mathematicians, physicists, engineers, chemists, biologists, computer scientists, and others will be part of the graduate faculty.

We see clear linkages with courses in the existing graduate programs of Imaging Science, Computer Engineering, Astrophysical Sciences and Technology, Computing and Information Sciences, and Sustainability. In addition, Ph.D. students in Mathematical Modeling and Scientific Computing will be able to avail themselves of classes from the Applied Mathematics Master of Science program for electives. Some of the existing M.S. classes will be updated to better mesh with the Modeling and Computation program. In addition to Mathematical Modeling and Scientific Computing students taking classes in other programs, we expect that the new elective classes will be accessible for some of the students in the existing Ph.D. programs discussed above. Consistent with other Ph.D. programs at RIT, it is expected that no more than five courses, including core and elective, will be taught per semester.

Ph.D. students who have completed their MS degree requirements will be allowed to hold Teaching Assistantships. For the university, the investment made in the students can be partially repaid through teaching. The Teaching Assistants (TAs), who have earned their MS degree, will assist the college in backfilling some of the undergraduate courses vacated by faculty teaching the new graduate courses and may reduce the need for adjunct faculty members. Teaching Assistantships will provide our students the opportunity to develop professional skills suitable for both academic and industrial jobs. Through teaching, our students will be able to develop further insight in their field, refine their communication skills, and practice the ability to select and organize content in a meaningful way. We believe the improvement in teaching will feed into the advancement of our students' research and the advancement of research will improve students' teaching. Before entering the classroom, our students will be required to participate in a teaching workshop; will be assigned a faculty-teaching mentor; and will meet with an instructional design consultant. Our student teachers will be observed in the classroom and mid-semester student surveys will be conducted to provide constructive feedback. We will work with the Teaching and Learning Serves in the Wallace Center to develop an effective Teaching Assistantship workshop.

In addition to course development spurred by the Mathematical Modeling and Scientific Computing Ph.D. program, we foresee that the program will provide enhanced scholarship opportunities for all levels from undergraduates to faculty. For faculty members, the program will provide the personnel required to form larger, more stable long-term research groups that can aid with establishing a consistently funded research program. For both Masters-level and undergraduate students, the presence of more senior graduate researchers to act as mentors and in advisory roles will provide a critical link in their development as researchers and will provide continuity and a degree of institutional memory with regard to student research that is difficult to achieve with students who have no more than one or two years to work on a project before graduating.

SPACE AND OTHER RESOURCES

Due to their small sizes, the new courses introduced for the Mathematical Modeling and Scientific Computing program may make use of small classrooms and conference rooms that are unsuitable for larger undergraduate classes. Modeling and Scientific Computing classes themselves will require no additional classroom infrastructure beyond those required for typical undergraduate classes (network access, projection systems, whiteboards). The proposed Ph.D. program will also make use of elective courses from the Astrophysical Sciences and Technology, Imaging Sciences, Color Sciences, and Computing and Information Sciences programs. These programs can provide application domain-specific courses that can be of interest for particular research projects.

To support the educational goals of the Mathematical Modeling and Scientific Computing program, a high-end computing environment, consisting of 12 to 16 computational cores and 2 high-end Graphical Processing Unit (add-on) cards will be purchased for a modest cost of $10,000. Space in an existing computer lab or data center will be needed to house this computer. The Modeling and Scientific Computing students will also make use of existing computer laboratories in the COS.

Office space for new faculty will not be needed because it is expected that new hires will replace retiring faculty members (incremental increases in the number of faculty are not anticipated). Space will be required for Ph.D. student offices, postdoctoral fellows, and lecturers. Initially, space for four students will be needed, increasing each year to a steady-state of 16-20 students. The Mathematical Modeling and Scientific Computing program will also need access to a conference room; conference rooms can be shared.

Students in the Mathematical Modeling and Scientific Computing program will have the opportunity to work with faculty members of the nine COS research centers to benefit directly from the research infrastructure provided by those centers. Two large research centers, the Center for Computational Relativity and Gravitation, and the Center for Applied and Computational Mathematics, will be involved directly with the proposed program. Facilities include meeting rooms, seminar programs, and visitor programs.

CONCLUSION

Current problems in sciences and technology are of such size and complexity that their solution requires sophisticated techniques drawn from computational and applied mathematics as well as the increasing participation of mathematicians in the interdisciplinary teams of scientists that attack them. Mathematics used together with high-performance computers can help model and simulate complex real systems and solve and interpret difficult equations that govern complex mechanisms inherent to many fields such as the biological sciences, computational neuroscience, computational physics and astrophysics, scientific computing, medical sciences, defense, social sciences, traditional business and e-business solutions, economics, reconfigurable devices and materials development, medical devices and drug delivery, and the prediction and function of financial systems. Because this specialty is essential in the mature computer age and because no current program exists that focuses on the development of models in a mathematical context, RIT should offer a Ph.D. program in Mathematical Modeling and Scientific Computing.