

# Program Structure

## 1 Education and training

The goal of this proposal is to spur innovation in mathematical research, to produce scientists ready to attack both "academic" and "real-world" problems (insofar as these are ever distinct) which do not fit neatly into a given academic discipline, and to produce educators and leaders in areas requiring broad scientific expertise. We feel these goals are best served by providing students in the theoretical sciences with a large toolkit, a broad exposure to scientific problems, experience in interacting with scientists in a variety of disciplines, and experience in communicating these ideas to the public. These objectives define the two-fold training goal of this IGERT. First, we wish to provide students with a wider set of computational tools than they are traditionally exposed to. We envision that the exposure to these tools in the context of problems in different disciplines will boost their own research potential. Secondly, we wish to expose students to a wide variety of problems outside of their official discipline. Our intention is to motivate students to work outside traditional boundaries during and after their graduate career. The IGERT will offer a sustaining environment and build a community that will support this type of research.

The IGERT trainees for this program will be PhD students in mathematics, physics, economics, neuroscience, biology, psychology and chemistry, who engage in theoretical/mathematical work via analytic or numerical techniques. We believe a disciplinary education teaches crucial lessons: the importance of attention to, and knowledge of a body of phenomenological details pertaining to a scientific problem, and the importance of informal lore and oral tradition in addition to published results. Therefore, the IGERT program will be built as a superstructure over the PhD education within their home department, and their PhD advisor will remain their primary mentor. In order to help reinforce their contact with the interdisciplinary activities of the IGERT program, however, each student will have a "co-advisor" from outside of the student's home department, as described in §7.2

The detailed education program of this IGERT has three components: a curricular component consisting of classes, research rotations, and summer institutes, a co-curricular component consisting of seminars and IGERT group meetings, and an education and public outreach component. We will also encourage students to avail themselves of outside internships. The IGERT faculty will work with the Hyatt Career Development Center at Brandeis, to develop internship opportunities using the existing network of connections between Brandeis faculty and non-academic research institutions. In addition, as described in the section on international activities below, we will provide an opportunity for an internship at the International Center for Theoretical Sciences in Bangalore.

### 1.1 Curriculum

The IGERT curricular program consists of the following components: a set of "breadth requirements" consisting of courses outside of the student's home department; a set of research rotations; and a yearly 2-week intensive summer institute put on jointly with the New England Complex Systems Institute. Each student will work with the IGERT steering committee and participating faculty in designing an individualized program that fulfills the curricular requirements, is consistent with the interdisciplinary goals of the IGERT, and fits their abilities and schedule. We will describe each curricular component in turn and then explain how the students will satisfy these requirements, and still meet the demands placed on them by their own departments. The program does rely on our ability to free the students of non-curricular departmental obligations during the first year by funding the students through the IGERT.

**Research rotations.** We wish to quickly expose IGERT students to problems and methods in fields outside of their discipline. We know of no better way to do this than to have them directly involved in research, much as total immersion is the most effective way to teach a language. Research will rapidly expose students to the types of problems a discipline finds interesting; the modes of attacking these problems; and the oral tradition and informal lore surrounding a field. These experiences will make their later interdisciplinary coursework, and the IGERT research seminars, all the more meaningful and effective.

We therefore will require four nine-week research rotations, typically taken during the first two years at Brandeis. Such research rotations are standard in the life sciences and were a very successful part of the Quantitative Biology IGERT grant. At least one of the projects must be of an analytic nature and one of a numerical nature; one of the rotations can take place at the NECSI; and at least two must be outside of the student's home department. At the end of each rotation, each of the students will give a short presentation to the entire body of IGERT students and faculty. This should help train the students to describe their work to a broad scientific audience.

The rotation requirements will be monitored by the IGERT Steering Committee (consisting of the co-PIs: see the section on management below), who will work with the students to develop an appropriate sequence and scheduling.

**Coursework.** IGERT students will follow the required sequence of courses and qualifying exams in their home departments, which typically spans two years and is most intense during the first year. IGERT students should also spend some time in deep study of another discipline, learning the language and basic assumptions of that discipline. Therefore, in addition to research rotations, we will require that they take at least *two* of the following courses, one of which must be outside of the student's home department. These will generally be taken in the student's first two years. Our hope is that these courses will have several IGERT students from multiple home departments at any given time, giving the IGERT students the chance to learn the subject together (and from students in the course's home department), so as to build a cohesive group and a common language for further group-wide activities.

The courses we have chosen are taken from existing courses in the Brandeis catalog. Many are offered every other year, and we have deliberately kept the number of courses offered per year small so that IGERT students take the courses together. Most of these course are already taught by faculty associated with this proposal, and there is a commitment by the faculty to redesign these courses to make them more meaningful for a cross-disciplinary audience. Furthermore, we have dedicated funds in the first-year supplement allowing pairs of faculty to develop four of the courses below as "team-taught" courses. The additional faculty member will provide perspective on the students outside of the course's home department. The participating faculty will better train themselves in the language of each other's discipline, and so make themselves more effective members of the IGERT program. The goal of this team-teaching is to develop a modernized and interdisciplinary curriculum. After the first team-taught effort the redesigned courses should be teachable by faculty from multiple IGERT-related departments. Thus, the new curriculum can be institutionalized at Brandeis beyond the life of the IGERT. In this way, we hope that a lasting effect of the IGERT is to create a more interdisciplinary curriculum at Brandeis, with faculty better trained to teach it. This is consistent with the ongoing consolidation of the sciences at Brandeis.

Below we list the specific courses, including which will be team-taught and when appropriate how they will be re-engineered for the IGERT. The sentences in italics are capsule descriptions from the Brandeis catalog.

1. FIN 285a: "Computer Simulations and Risk assessment." *Examines recent advances in computational methods for evaluation risk and decision making in risky situations. Emphasizes a common computational framework for solving many problems from business, finance, and economics using statistical methods, such as Monte Carlo and resampling.*
2. MATH 56a: "Stochastic processes". *Basic definitions and properties of finite and infinite Markov chains in discrete and continuous time, recurrent and transient states, convergence to equilibrium, Martingales, Wiener processes and stochastic integrals with applications to biology, economics, and physics.* This course will be team-taught in the first two years of the program.
3. MATH 211a/221b. 211a: "Topics in differential geometry and analysis". *Possible topics include complex manifolds, elliptic operators, index theory, random matrix theory, integrable systems, dynamical systems, ergodic theory.* 221b: "Topics in Topology". *Topics in topology and geometry. In recent years, topics have included knot theory, symplectic and contact topology, gauge theory, and three-dimensional topology.* The boundaries between these courses are indistinct so we list both; in a given year the steering committee will decide which is an eligible course based on the curriculum. MATH 221b will be team-taught in the first two years of the program, as a course in "computational topology" [67], using algebraic topology to understand and analyze large multi-dimensional data sets. (The

mathematical background for the projects in §3.2.3 can also be taught through 211a or 221b. We feel that this will not require team teaching.)

4. NPHY 115a: "Dynamical Systems". *Advanced introduction to the theory of nonlinear dynamical systems, bifurcations, chaotic behaviors, and fractal patterns. Concepts and analysis are illustrated by examples from physics, chemistry, and biology. The course will be complemented by a significant number of computer labs.* This course was originally developed for the neuroscience program, and it will be team-taught in the first two years of the program, in order to update it for a more general audience.
5. PHYS 110: "Mathematical Methods". *A selection of mathematical concepts and techniques useful for formulating and analyzing physical theories. Topics may include: complex analysis, Fourier and other integral transforms, special functions, ordinary and partial differential equations (including their theory and methods for solving them), group and representation theory, and differential geometry.* This is a course currently under intense discussion by the Physics department's curriculum committee. Therefore there is an opening to changing or expanding the possible topics to include those that would be of interest to IGERT students, such as analysis of stochastic equations, information theory, and signal processing. This course will be team-taught in the first two years of the program.
6. PHYS 202a, "Quantum and Statistical Field Theory". *Methods of statistical and quantum field theory, including path integrals, second quantization, Feynman diagrams, renormalization group, epsilon expansions, effective field theory. Applications ranging from phase transitions and critical phenomena to gauge theories of particle physics.* Quantum and statistical field theory are formally nearly identical and each is informed by insights from the other. Over the past eight years, this course has been taught (by Prof. Lawrence) to a dual audience of prospective particle physicists, astrophysicists, and soft condensed matter physicists, and the resulting course is adaptable to the IGERT audience.
7. QBIO 110a, "Numerical Modeling of Biological Systems." *Modern scientific computation applied to problems in molecular and cell biology. Covers techniques such as numerical integration of differential equations, molecular dynamics and Monte Carlo simulations. Applications range from enzymes and molecular motors to cells.*
8. BIOL 135b, "Principles of Modeling in Biology." *Highlights the common mathematical underpinnings of concepts found throughout biology, such as oscillations and waves; homeostatic control; and the usefulness of variability/noise. Computer models of example systems span levels of scale, from genetic mutations to enzymatic reactions to neural synchronization to predator-prey interactions. (Usually alternates years with QBIO 110a)*

To ensure that the team teaching is not an undue burden on the faculty or on the curriculum, the grant will pay one month's academic year salary to the outside instructor. In return, the Dean has agreed that this course will count as a full semester's course for both instructors, in terms of their load. Note that we have listed co-PIs Ruberman and Chakraborty in the budget. In practice the specific assignments and timing will follow from the Division of Science's curricular planning if the grant is awarded.

**Summer research course.** During the summers of their second or third years, the students will be required to attend a (2-week) summer "boot camp" which will consist of intensive lectures, 5-10 hours per lecturer, on a variety of subjects, by leaders in the field. As described in §5.2, the Dean of Arts and Sciences has provided some funding to bring in lecturers from outside of the Boston area (since these cannot be funded by the IGERT program). We intend this summer experience to provide strong bonding opportunities for the IGERT students. Successful models for these are the 1988 and 1994 Les Houches summer schools which combined string theory, hard and soft condensed matter physics, gravitational physics, and pure mathematics. These courses will be offered in partnership with the NECSI. The NECSI currently offers three, intensive week-long summer courses (*cf.* <http://necsi.edu/events/summer2009.html>). IGERT students will be required to take one of these NECSI courses, chosen by the IGERT PIs, which will be combined with a 1-week course that will be offered at Brandeis. The 2-week institutes will also be opened to interested non-Brandeis students. Registration fees from these students will be used to fund travel and living expenses for speakers from outside of the Boston area.

A sense of what might be offered in the first week can be gleaned from the 2009 NECSI courses, which were:

1. "Fundamental concepts of complex systems": Collective behaviors, descriptive complexity, multiscale representations, evolution, with applications to physical, biological and social systems.
2. "Modeling and Networks": Computer modeling of complex systems, characterization and dynamics of real world networks.
3. "Mathematical methods": iterative maps, stochastic processes, markov chains, cellular automata, stochastic fields, Monte Carlo simulations, information theory, computation theory, scaling, fractals and renormalization, linear stability analysis, pattern formation, and mean field theory.

This last course is a good example of a boot-camp form presentation of the mathematical methods that are recurring themes in our proposal.

For the second week, Brandeis will coordinate with NECSI to present complementary material in these courses. Possible subjects for the Brandeis course include: First passage time theory, Phase-plane analysis, Stochastic resonance, Extreme value theory, Bootstrapping, Schramm-Loewner Equations, Instanton methods in field theory, Supersymmetry, and Ricci flows in mathematics and physics.

The lectures will be at a level similar to lectures at a graduate student-oriented summer institute (such as TASI or Les Houches). This format, the participation of NECSI, the outside lecturers, and the outside students, will facilitate contacts with the outside world. One advantage of current summer schools such as Les Houches or the Boulder TASI schools is precisely that young scientists often meet each other for the first time there and begin forming valuable networks.

Our hope is that this becomes a worthy successor to the famous Brandeis summer schools in theoretical physics which were extremely influential in the 1960s and early 1970s. Indeed, it has been suggested to the PI by several senior physicists that these schools be re-started. However, there are now many successful summer institutes in particle physics and other disciplines: TASI, the IAS Park City summer school, Prospects in Theoretical Physics at Princeton, and so on. We feel that the interdisciplinary nature of the IGERT summer institute would provide a distinct and important service to PhD science training in the US, which is the main reason we wish to open the schools to outside participation.

## 1.2 Co-curricular activities

We have planned both seminars by outside speakers, and internal group meetings, with the twin motivation of exposing IGERT students to a variety of problems across the disciplines, and of teaching students both to communicate their results to a broad audience, and to be able to participate actively in seminar-level discussions.

1. **Blackboard lunches.** Once per month, there will be a group meeting which the IGERT students will be required to attend. These will take the form of a short, informal blackboard presentation by a senior (third through fifth year) graduate student, and discussions of the subject amongst members of the group. This structure has been fairly successful in the current Brandeis IGERT in quantitative biology, and we feel it will be worth replicating in our program. All IGERT faculty will be encouraged to attend all of these talks. The students making the presentations will meet with their committee immediately after these talks to discuss technical and presentation aspects of the seminar in order to strengthen the impact of the experience on their overall training. We view this part of the program as critical: opportunities for presenting and defending ones work orally are one of the most important aspects of a graduate education. This program will serve the dual role of teaching the students to communicate effectively with a broader (but still theoretically trained) audience than people in their research groups, and will provide additional intellectual glue, apprising the IGERT students and faculty of each other's research.
2. **Research rotation presentations.** At the end of each semester and the end of the summer, the students who have completed research rotations will each give a short presentation of the results of their work. This meeting will be attended by all IGERT faculty and students.

3. **Seminars.** It is important that IGERT students and faculty maintain contact with the community outside of Brandeis. Once per month, there will be a designated IGERT seminar, typically by a non-Brandeis speaker, on a topic of current research. This seminar series will be student hosted, and IGERT students will invite speakers in consultation with one of their faculty advisors. The emphasis will be placed on speakers who would not typically give a talk at research group seminars; and on speakers who would be able and willing to speak to a broader audience than a typical research group seminar.

### 1.3 Overview of the PhD program and sample curricular plans

In addition to the above requirements, the students must fulfill their obligations and requirements to Brandeis and to their home department.

1. **Teaching Experience.** Teaching assistantships are an important and valuable part of training students to be good educators. At least two semesters of such assistantships are also required in many degree programs. Therefore, all IGERT trainees will serve as teaching assistants for two semesters during their first two years.
2. **Thesis committee.** All IGERT students will have a thesis committee picked during their first year which will include their thesis advisor and at least two faculty affiliated with the IGERT program, one in their home discipline, who can be the thesis advisor, and one in a separate department, who will be the student's co-advisor (described in §7.2 below). This committee will meet with the students once per semester and once during the summer, to monitor the student's progress in research and their participation in the IGERT program.
3. **Steering committee sessions.** The students will meet the IGERT steering committee once per year to give a short presentation of their work and discuss their progress within the IGERT program as well as within their home PhD program. The committee will help the student shape the details of their program. These meetings will be discussed further below in the context of mentoring and retention.

#### IGERT program tracks

In terms of scheduling IGERT activities for each student, IGERT funding will free up time for IGERT curricular activities. For most students these activities will begin in the first year. Students who become interested in this program after their first year, or students in mathematics who undergo extensive teacher training in their first year, will begin their research rotations in the summer after their first year, into their second and third year. Students who complete a full year of teaching in their first year will not teach in their second year. They therefore will have the time to catch up with the other students by the middle of their second year.

During the first year, the interactions of students will primarily occur through the lunches and seminars, and the summer institutes since most students will be occupied with required disciplinary activities. Students will begin research rotations during their first year, unless they are recruited in their second year or need to meet departmental requirements beyond the usual courses.

In terms of detailed scheduling of the IGERT requirements, we have tried to provide some flexibility. Different students have different preparation levels, and it is possible that we will select some students from the existing first-year classes if they show promise. Different disciplines have different characteristic "start-up" times between when the student begins graduate school and when they are ready to pursue advanced research. Different departments require different distributions of effort over time. To get a sense of how the students will balance the IGERT program and their own departmental degree program, we have provided a few sample "tracks" below. These are just examples and each student will design his or her program in consultation with the IGERT steering committee. However, they illustrate how we might mix the students, and how we would provide the "outside the box" training central to this IGERT proposal.

- **Mathematics PhD student** Year 1: Extensive teacher training (required of all Math students); disciplinary courses; summer rotation. Year 2: Take FIN 285a, and either MATH 56a or MATH 211a/221b); 1 research rotation (Fall or Spring). Year 3: 2 research rotations.

- **Physics PhD student** Year 1: Disciplinary courses; 2 research rotations. Year 2: Take either MATH 56a or MATH 211a/221b, and FIN 285a; 2 research rotations.
- **Chemistry PhD student** Year 1: Disciplinary courses; 2 research rotations. Year 2: Take QBIO 110a (or BIOL 135b), PHYS 110a; 2 research rotations.
- **Life Sciences PhD student** Year 1: Disciplinary courses; 4 research rotations. Year 2: Take MATH 56a and either PHYS 110a.
- **IBS PhD student** Year 1: Disciplinary courses; 2 research rotations. Year 2: Take MATH 56a and either QBIO 110a or NPHY 115; 2 research rotations.
- **Psychology PhD student** Year 1: Disciplinary courses; 4 research rotations. Year 2: Take NPHY 115 and PHYS 110a (or BIOL 135b).

#### 1.4 Broader impact: public outreach

In their careers beyond Brandeis, we wish the IGERT students to be both first-rate scientists and first-rate educators. In addition, a publicly funded enterprise has a duty to report its work to the general public, and to further the inclusion of traditionally underrepresented groups into the scientific community. Aiming at these goals, IGERT students will participate in the following activities:

**Saturday Morning Lectures.** Once per month during the academic year, Brandeis will offer a Saturday morning lecture for members of the nearby community, including high school teachers and students. Two lectures per year will be by senior IGERT students, following careful coaching and rehearsal with the IGERT faculty. The rest of the lectures will be delivered by Brandeis faculty and postdocs, on a rotating basis. A student and faculty assistant, also rotating from month to month, will be the project coordinator with the organization. We will leave ample time for discussion between the audience and members of the IGERT students and faculty. We will advertise through local media. We will also use existing contacts such as Headrick and Lawrence through their participation in the NSF Theorynet program, and Chakraborty's contacts with the Lowell Regional Physics Teachers Alliance to attract interested high school teachers and students.

**Brandeis Science POSSE program.** The Brandeis Science Posse program gives scholarships to ten students from New York City with the intention that they attend Brandeis as a group and focus on science. These students are chosen for their academic ability and leadership skills. The geographic focus gives cohesion to each cohort, and ensures a diverse group each year. This program is run by Prof. Irv Epstein together with the Posse Foundation, and is currently partially supported by a \$1 million grant from the Howard Hughes Medical Institute. Currently, the Posse scholars begin with a 2-week summer "boot camp". We will direct the IGERT graduate students to either assist with the boot camp, or help advise Posse scholars during their time at Brandeis.

**Acton Discovery Museum.** The Discovery Museums in Acton, MA are hands-on interactive museums, which include a science museum for both children and adults. As part of the outreach program for the Brandeis MRSEC grant, Prof. Michael Hagan and Prof. Zvonimir Dogic (a soft condensed matter experimentalist) and their research groups have begun a series of demonstrations with the aim of constructing an interactive exhibit around the dynamics of biological systems. Much of this interacts with the themes of this IGERT proposal – the intent is to build exhibits around the Brownian motion and eventual self-assembly of interacting colloidal particles; and adjustable simulations of viral capsid assembly which allow the users to explore the problem at different scales. The IGERT students and faculty will combine forces with the Hagan and Dogic groups in aiding with the presentations, developing material for the exhibits, and training secondary school teachers.

#### 1.5 Internship opportunities

One purpose of this proposal is to expose the students to scientific problems outside of an academic setting. In part this is because we envision that many of our students for careers in industry and public

policy. Furthermore, we feel that this exposure will be intellectually enriching for students who remain in academia, by exposing them to new problems and new perspectives. We will therefore encourage interested advanced students to seek out private-sector internship possibilities. This is already something that is done by economics students. For the others, we will work with the Hyatt Career Development Center at Brandeis to develop internship possibilities using existing private sector connections amongst the faculty.

In §2 we will also describe our partnership with the International Center for the Theoretical Sciences in Bangalore, India, to provide funded research internships for interested students. This will expose them to a vibrant research community in a rapidly developing country.

## **2 International Collaboration**

It is important for students to become exposed to the global nature of scientific research and to develop contacts with other research communities. In doing so, we feel it is best to leverage existing connections with strong research groups. Many participating faculty, including Chakraborty, Headrick, and Lawrence have strong ties to the Indian scientific community. Furthermore, Brandeis is consciously focusing on India in developing global outreach and education programs, through its India Initiative. While the focus has so far been on undergraduate recruitment and education, the Office of Global Affairs is interested in widening these activities to include graduate education and outreach. For more on the India Initiative, see <http://www.brandeis.edu/globalbrandeis/regions/india.html>.

Within this context we have found an ideal partner. The International Center for the Theoretical Sciences in Bangalore is a new institution designed with a scientific outlook very close to that of this IGERT. This center runs research-level programs across the mathematical sciences, and has a roster of world-class affiliated faculty from all over the country. The ICTS is very eager to host Brandeis IGERT students, as described in the attached letter. We will therefore provide interested students late in their graduate career (at the earliest, at the end of their third year) with the opportunity to do a semester-long internship at the ICTS. The students will select a local faculty advisor, from the affiliated ICTS faculty or from faculty attending specific programs. The foreign advisor will be asked to submit a one-page evaluation at the end of this internship, for the benefit of the IGERT steering committee and the student's PhD thesis committee. Before embarking on their internship, students will attend a short orientation program at Brandeis (consisting of several lectures and discussions over the course of a week or two), offered by the Office of Global Affairs.