(C) Project Description

a. List of Participants

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	P.J. Mucha, Assistant Professor, School of Mathematics	PJM
	G.P. Neitzel, Professor, School of Mechanical Engineering	GPN
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	E. Voit, Georgia Research Alliance Eminent Scholar in Systems Biology, BME	EV
	D.R. Webster, Associate Professor, School of Civil & Environmental Engineering	DRW
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	Minami Yoda, Associate Professor, School of Mechanical Engineering	MY
	H.M. Zhou, Assistant Professor, School of Mathematics	HMZ

Key to abbreviations used throughout the proposal:

AE	School of Aerospace Engineering
Bio	School of Biology
BME	Georgia Tech/Emory Biomedical Engineering Department
CE	School of Civil & Environmental Engineering
Chem	School of Chemistry and Biochemistry
CNS	Center for Nonlinear Science
CoE	College of Engineering
CoS	College of Sciences
EAS	School of Earth and Atmospheric Sciences
GT	Georgia Institute of Technology
Math	School of Mathematics
ME	School of Mechanical Engineering
Phys	School of Physics
PTFE	School of Polymer, Textile and Fiber Engineering

b. Vision, Goals and Thematic Basis

Nonlinear science impacts a broad spectrum of disciplines. Increasingly, researchers face complex problems having no clear boundaries between physics, mathematics, engineering, and life sciences. Of the six "grand challenges" identified in a recent National Research Council report [1]; three of these – "understanding complex systems", "applying physics to biology", and "creating new materials" – demand conceptually new methods for dealing with dynamical systems with many degrees of freedom in complex, noisy environments. It is no accident that the Topical Group on Statistical and Nonlinear Physics and the Activity Group on Dynamical Systems are among the most active within APS and SIAM, respectively.

Only a broad cross-disciplinary effort can make headway here. In order to prepare young researchers for these challenges, we propose to enrich their education by offering training tools and methods of nonlinear science that remove departmental boundaries and bridge academic and industrial research. We envision the IGERT **Dynamics in Many Dimensions** program fostering:

- **Cross-cutting research initiatives, with nonlinear science as the unifying theme**, based on common concepts which unify a broad range of problems in basic science. GT has an exceptionally strong community of experts in high-dimensional dynamics: fluid mechanics, pattern formation, turbulence, stochasticity, interface motion, nanofluidics, nonlinear control, and dynamics of organisms living in turbulent flow environments. Research and advanced training will be cross-disciplinary, emphasizing the diverse range of applications and solutions to be found in many fields, from math and physics to engineering.
- **Training in cross-cutting methodologies**, stimulating cross-disciplinary research and communication skills through a balanced core curriculum that includes both lecture-based and project-based courses. The curriculum draws from existing courses and develops new ones. A key innovation is an early research experience, carried out in small teams guided by faculty members with complementary perspectives. The IGERT program will form the core of a vibrant, highly cooperative environment through a combination of cross-departmental research seminars, student-run seminars, regional workshops, and a visitor program. Global perspective will be enhanced through internships and summer schools with sister institutions abroad.
- **Outreach**: GT has a notable record in minority recruitment and retention [2]; the IGERT program will encourage undergraduates from historically black Atlanta-area colleges to chose a career in science or engineering, by involving them in IGERT summer research projects. Another outreach component is service-learning. Each IGERT fellow will contribute to the Atlanta community through one of the following activities: research/teaching internships with Spelman College (an HBCU), developing and presenting a nonlinear science teaching module to local high school students, or comparable service by creating her own individual or group project. Educational outreach will be also served by the development of a web-based advanced nonlinear science course.
- **Strategic impact**: GT is the premier science and technology institution in the Southeast, with strong state and industrial support. Already possessing a leading program in nonlinear science, GT teams up faculty in cross-disciplinary facilities and is moving aggressively into several allied areas, establishing new centers in nonlinear science, bioinformatics, biomedical engineering, molecular sciences, and large scale computing. The IGERT program builds on and draws together these diverse innovative initiatives.

The IGERT program will offer advanced nonlinear science training and a highly cooperative and cross-disciplinary environment to IGERT Fellows. A new program which synthesizes research, lecture, workshop, and internship components will enrich their graduate degree programs.

PROJECT GUIDE FOR DYNAMICS IN MANY DIMENSIONS

After selection as an IGERT Fellow [April, Calendar Year 0]:

- Contacted by Assistant Director of IGERT program
- Assigned a peer mentor

First month of program [August, CY 0]

- IGERT Welcoming Orientation/Retreat (1 day)
- Nonlinear advisor/mentor matched to student at orientation

Overview of IGERT Educational Program [August, CY 0 through July, CY 3]

Acad. Yr	Cross-Disciplinary Coursework	Activities Common to All Fellows		Additional Opportunities
1	Level (0)[a]: course exposing biology students to necessary mathematical skills. Level (1)[b]: required introductory nonlinear science course.	Welcoming Orientation	Workshop[f] IGERT Research Seminars[g]	CNS[h], GW/GM Seminars[i] Summer school in nonlinear science[j] Apply for seed money[k] Apply for international internship[l]
2	Level (2)[b]: advanced elective courses.	Service learning[d]		
3	Level (3)[b,c]: group projects, thesis research	P&E Seminar[e]		

a. Level (0): Mathematical Modeling is geared to bring mathematical and quantitative talents of biologists to routine use in research problems. See also section C.d.ii
b. Levels (1), (2), (3): see section C.d.ii
c. Research advisor selected after development of research topic
d. One semester of: teaching at local HBCUs; high school educational module development; or independent service project
e. Professional & Ethics Seminar: weekly (one semester) seminar run by Asst. Dir.
f. Southeastern Nonlinear Science Workshop
g. Biweekly seminar run by IGERT fellows; each student will present annually
h. Center for Nonlinear Science Seminars: weekly ongoing seminar run by faculty
i. Graduate Women's and Minority Seminars: see section C.g
j. Summer Nonlinear Science School
k. Provide funds directly to student for research needs via competitive grant awards.
l. See section C.i: to promote international exchange.

c. Major Research Efforts

Existing methodologies of nonlinear science form the core of the training proposed under this IGERT program; insights into low-dimensional dynamics have changed our ways of thinking in profound ways, and need to be taught to every engineering and science student, as a part of their basic tool kit. Most of the available lower-dimensional tools largely fail for systems involving many strongly coupled degrees of freedom. Many of the exciting developments in high-dimensional/stochastic research are new, and therefore have yet to diffuse across disciplinary boundaries. The faculty interactions that made us aware of the commonality in our research, and the need for common training (that eventually led to this IGERT proposal), arose almost by accident, through graduate students taking advanced courses outside their own Schools.

Conceptually new methods applicable to systems with high numbers of deterministic degrees of freedom as well as to mixed systems of chaotic, integrable, and stochastic components need to be developed; the present lack of such methods remains a fundamental barrier to the direct application of techniques from nonlinear science to many important outstanding problems. Our IGERT will seek to break this impasse by bringing together teams of IGERT Fellows and faculty with complementary experimental, numerical and theoretical skill.

In what follows, the core GT and international faculty listed on page 1 are indicated by initials (i.e. [LAB] for L.A. Bunimovich). The core faculty will take part in Fellow co-advising, new course development, collaborative research, as well as other key IGERT activities. The international faculty have been carefully selected for their committment to interacting with GT (making frequent visits to deliver a mini-course to IGERT Fellows, for example), and to hosting IGERT interns. The number of active IGERT faculty already exceeds the NSF limit of 20 senior personnel, so not all of the faculty CVs are included in this proposal. Furthermore, given ambitious GT hiring plans in this area, we expect a significant number of new faculty to join the IGERT over its five-year span. The number of the students benefiting from the IGERT stimulated research will also be significantly larger than the 25 IGERT Fellows directly supported by this grant.

All the research under this IGERT addresses the same grand challenge of high-dimensional dynamics: the role of *patterns and coherent structures in high-dimensional dynamics*, and the interplay between *stochasticity and nonlinearity*. These topics (as will be seen in the following brief sketches) cannot be neatly grouped into separate Major Research Efforts. The research challenges may arise across different disciplines, but they all urgently need new analytic and data analysis tools.

High-dimensional dynamics – observations: In their research, the IGERT faculty explore a broad range of high-dimensional phenomena, on scales ranging from very large systems to very small. What most of these problems have in common is that they are spatially extended systems with very many coupled degrees of freedom. The dynamics of these systems can range from ordered (pattern formation near onset) to highly disordered (fully-developed turbulence).

Satellite observations of the past decade are giving us increasingly detailed, high resolution information about the **turbulent dynamics of oceans**. The images show ocean surfaces of a very complex texture, with a rich repertoire of coherent patterns and vortices. Marine ecosystems are strongly affected by ocean turbulence. This is evident from satellite maps of surface *chlorophyll-a*, which show a rich texture of filaments associated with the eddy field (Fig 1). In the coastal ocean, where biological activity is higher, the complex coastal geometry gives raise to new classes of eddy generating mechanisms. Recent observational and modeling studies [EDL] along the North Pacific eastern boundary suggest that such oceanic variability is tied in with the anomalies in salinity and nutrients. However, at this time the links between the geophysical fluid dynamical instabilities and their effects on nutrients, larvae and spawning habitats are not clearly established, due to the highly nonlinear response of the higher trophic levels of the marine ecosystem.

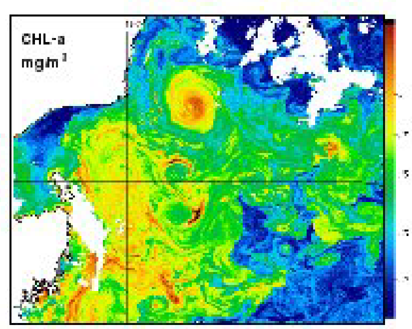

Figure 1: *The SeaWIFS satellite observation of* chlorophyll-a *concentration.* `www.marine.csiro.au/~lband/SEAWIFS`.

This poorly understood nonlinear response of a biological system to changes in the physical environment has motivated the funding of an NSF Long Term Ecological Research (LTER) site for the study of non linear transitions in the California Current pelagic Ecosystem. EDL, who is leading the modeling effort associated with this LTER (development of Navier-Stokes solvers for particular oceanic settings), has elucidated the mechanism by which the oceanic warming trend along the California Current may contribute to the sharp decline in zooplankton. [3] Declines such as these have tremendous impact on fisheries and worldwide economy, especially as we face the challenge of global warming, where the properties of the earth systems are changing dramatically compared with what we have seen in the last few millenia. While low-dimensional nolinear dynamics has had some degree of success in the study of important atmospheric-oceanic systems like El Niño, *the physical-biological interactions, as well as the ocean-atmosphere coupled climate modes, are prime examples of highly complex systems for which new tools to elucidate high-dimensional dynamics urgently need to be developed.*

At a more fundamental level, PKY carries out some of worlds's largest direct numerical simulations of the Navier-Stokes equations, employing more than 10^9 grid points, in order to elucidate **turbulent diffusion and mixing** in the atmosphere. [4] In this highly collaborative quest, PKY is joined by K.R. Sreenivasan and others (see the appended ICTP letter of intent). At an order of magnitude smaller spatial scales, CAK seeks to uncover the general principles underlying the striking **patterns in space, time, and organization observed in ecosystems**. [5] CAK group seeks to understand the role of spatial heterogeneity on species competition and coexistence, and the dynamics and the origin of regular and irregular patterns in settings such as semiarid vegetation. Low-dimensional population dynamics models by theoretical ecologists, notably Sir Robert May [6], pioneered the chaos theory. The challenge today is analyzing high diversity, multi-species ecologies, with hundreds of interdependent species spread over a complex, spatially extended habitat, affecting the flux of energy and nutrients through the ecosystem.

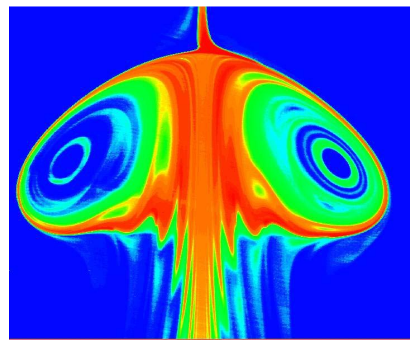

Figure 2: *The vortex breakdown flow: Poincaré map extracted from experimental observations of the flow. [DRW and F. Sotiropoulous]*

In his **Environmental Fluid Mechanics Laboratory** (an IGERT training facility, described on page 32) DRW observes hydrodynamical fluid flows [7] exhibiting unstable vortices of striking beauty (Fig 2). On the scale of centimeters, PJM is developing microscopic and macroscopic models of interacting particle systems in order to understand the **dynamics of neutrally-buoyant and sedimenting suspensions, granular materials and colloidal systems**. The goal is to apply the insights so gained to real slurry flows; simulations of sedimenting suspensions reveal surprisingly rich dynamics, [8] but in this endeavor, as well as in all numerical studies of turbulence, the bottleneck is the difficulty in resolving properly the small scales.

On the scale of millimeters, JY's copepods generate characteristic vortex wakes [9], illustrated in Fig 3. HY carries out *in situ* observations of interactions between oceanic turbulence and such micro-organisms [10]. On the applied mathematics front they are joined by TJP, whose higly acclaimed work on biological and medical applications of fluid dynamics is aimed, *inter alia*, at understanding the behavior of dense populations of swimming micro-organisms in turbulent environments. TJP group's simulations of the pairwise hydrodynamic interaction of "squirmers" (model micro-organisms) yield rational estimates of cell diffusivity. [11]

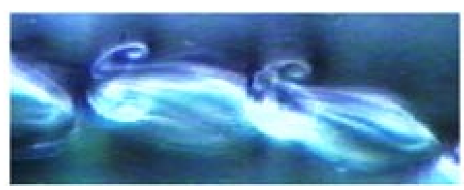

Figure 3: Planktonic copepods accelerate their swimming appendages up to $50 m/s^2$. Two vortices are created by 4 pairs of legs galloping twice within the field of view [9].

On still smaller scale, in their development of *opto-microfluidics*, MFS and RG study experimentally and theoretically mixing in optothermally manipulated microdroplets, induced by laminar rather than turbulent flows. [12] At the submicron scale, MY group is able to non-intrusively measure near-wall surface temperature fields in microchannel flows, and has developed "nano-particle image velocimetry" (nPIV), a new interfacial velocimetry technique for measuring velocity components in a flow within 250 nm of the container wall, despite sever Brownian diffusion effects [13]. KEK's highly interdisciplinary investigations of cement-based materials – complex visco-elastic materials with multi-scale structural heterogeneity [14] – rely on a whole array of novel imaging techniques to characterize damage propagation and fracture (tomography, confocal, x-ray, synchrotron). Her measurements are compared to GG studies of how the microgeometry of a material affects macroscopic properties of nonlinear composites, polycrystals and porous media. [15]

All the way down at atomic scales, ER pursues experimental nanomechanics and nanotribology with Atomic Force Microscopes: friction, adhesion, elasticity, wear. This ties in with the multi-dimensional theme of IGERT research through her observations of counterintuitive nanofluidic behaviors, phenomena with important implications for design of MEMS, "Labs on a Chip" and cell manipulation. [16] At these scales the validity of assumptions underlying continuum fluid dynamics has to be reexamined; the matter is of particular urgency at the cellular level [EV], where enzyme concentration can be extremely low, as low as 100 enzyme molecules in certain cells. At such small scale no textbook [17] rate laws based on the assumption of homogenous mixing apply.

What all of these puzzles have in common is that they are manifestations of dynamics of spatially extended systems, systems with very many coupled degrees of freedom. This wealth of observations provides the unifying focus of this IGERT: *"How to characterize and control high-dimensional, spatially extended, and very noisy dynamics?"*

Stochasticity & nonlinearity: In their attempts to understand their systems in terms of deterministic high-dimensional dynamics models, all of the IGERT faculty confronts the daunting problem of distinguishing what part of a signal can be ascribed to the underlying nonlinear dynamics, and what part is masked by (what is often a very significant level of) noise.

For example, in EDL's modelling described above, one needs to understand better the response of ocean circulation to stochastic forcing from the atmosphere, and to separate deterministic *vs.* non-deterministic response of flows in presence of complex coastal geometries. CAK faces the identical challenge in modelling populations within given complex habitats. In medium term **climate forecasts**, LAS group aims to achieve optimal weather prediction in the face of real, noisy data, with dynamical models that account for both chaotic and stochastic aspects of climate dynamics. [18] No less conceptually and practically important is the issue of ultimate limits to predictability within the attainable observational data. Still more difficult are issues of dealing with biological data, such as EV's biological time series data, typically short and not particularly dense, or PC's neuronal time series [19].

Even in a turbulent sea, a plankton can identify a prey, predator, or mate by the complex but characteristic wakes that bodies moving through fluid shed [JY,DRW]. How do such organisms recognize biologically created flows, distinguish them from background turbulence of comparable characteristic size? One surprising answer comes from what initially was a basic discovery [20] in nonlinear science [KW]. In vitro experiments [21] showed that hair cells exhibit *stochastic resonance*, a counterintuitive nonlinear phenomenon where detection of weak signals is *enhanced* by the presence of external noise [41], thus turbulence not only fails to obscure the message, but can help get it across, not only for living organisms but also in dispersal of pollutants through atmosphere [PKY,DRW].

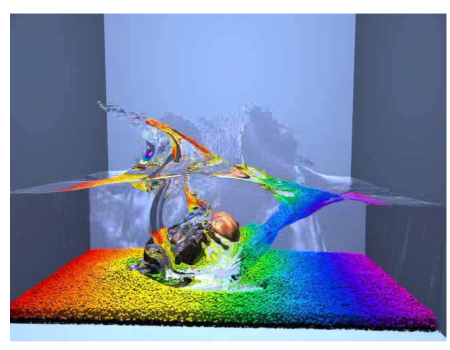

Figure 4: *Dynamical simulation of a stone hitting a fluid surface, by PJM and Computer Science PhD student M. Carlson. [22]*

A central question across many disciplines, and one of the driving questions motivating this IGERT is: *"How do unstable coherent structures manage to be so recognizable in a world so noisy?"*

High-dimensional dynamics – challenges: Theoretical and conceptual challenges in analysis, theory and implementation of control in high-dimensional dynamical systems that this IGERT intends to meet are threefold: visualization, dimensional reduction, and characterization of unstable coherent structures.

All of the research in high-dimensional dynamics grapples with the issue of **meaningful visualizations of physical phenomena**. PJM's development of physical rules for animating solid-liquid interactions efficiently, by means of a low-order distributed Lagrange multipliers method with the free surface treated with level sets, already yields beautiful visualizations of dynamics (Fig 4), visualizations that were beyond reach only a few years ago. [22] KEK 3-dimensional models of material microstructure need to be compared with video images generated by laser confocal microscopy (LSCM). Training and experimentation with such visualizations is a common need for all research pursued here (see IGERT Lab, Sec C.d.ii).

Dimensional reduction: HK has devoted considerable effort to the stochastic modelling of nonlinear deterministic time series under the influence of noise, with fast chaotic degrees of freedom replaced by suitable stochastic processes. Complex dynamical phenomena are experimentally recorded as time series, and HK group has applied such methods to physical, environmental and industrial issues. In collaborations with industrial companies the group implements noise reduction in problems such as speech signals for speech recognition programs, and the prediction of turbulent gusts in control and operation of wind farms turbines. LAS group is developing diagnostic nonlinear time series analysis applied to operational weather models, climate records and real-time forecasting of continental electricity grids. Among the leading nonlinear time series analysis groups in the world, the HK group in Dresden [23] and LAS Oxford/London group were invited to join this IGERT as Fellow international hosts, both for their close ties to GT researchers, and because they provide **dimensional reduction** expertise urgently needed for EV, EDL, PC, and CAK research effort, but currently not taught at GT.

Numerical explorations of systems such as hydrodynamics reveal a truly bewildering wealth of solutions. One needs to understand the instability mechanisms arising from the interplay between nonlinearity, transient dynamics, and stochasticity, often resulting in rather surprising dynamics. For instance, the onset of turbulence observed in shear flows occurs well within the ranges of Reynolds numbers, where the laminar flow is still linearly stable. Transient amplification in such systems leads to extreme sensitivity to noise, precluding any spatially localized control, even at unrealistically low levels of noise. [36]

Turbulent systems never settle down, but we can identify a snapshot as a “cloud“. How do we do it? In order to understand how such systems go turbulent, one needs to determine, classify, and assign relative importance to the coherent structures they exhibit. [24] This research is still in its infancy, but it has led to a working hypothesis that the dynamics explores an approximate *finite* alphabet of unstable recurrent patterns, a hypothesis which the IGERT program is uniquely poised to explore. On the one hand, periodic orbit theory [25] offers the mathematical implementation of this intuitive picture [TU,RG]. On the other hand, the MFS group possesses a unique skill: by means of their thermally actuated control of thin films [26] pioneered here [MFS] they are able to *design* spatio-temporal patterns, and thus create and test experimentally the patterns singled out by the theory. The IGERT teams need to quantify the dynamics underlying interaction of coherent structures in turbulent flows; the IGERT will address these challenges relying on experiments such as the real-time 3D optical measurements of wakes in fluids [JY,HY], and fluid dynamic simulations of such wakes [DRW,JP].

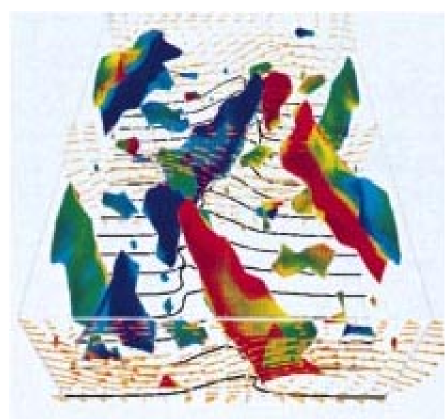

Figure 5: *A 3-d instantaneous snapshot of an unstable periodic solution embedded in Couette turbulence [27]. Vectors and color code velocities and vorticities.*

The experience and skills of IGERT's **computational fluid dynamicists** [PKY,DRW,EDL,RG] are absolutely essential for any further progress. Pushing the current limits of what is numerically attainable in solving large sets of PDEs, the “state of art” consists in writing down a set of hydrodynamical PDEs, discretizing the set on a mesh or a basis function set on the order of 10^4-10^9 components, and following trajectories in high-dimensional phase spaces. An example of what has been attained so far is the calculation by Kawahara and Kida [27]: the first demonstration of existence of an unstable recurrent structure in a turbulent hydrodynamic flow, in a *15,422-dimensional* numerical discretization of three-dimensional plane Couette turbulence at $Re = 400$ (Fig 5).

Why is IGERT essential to the success of the proposed research training? The challenge of high-dimensional dynamics simply cannot be addressed from the confines of a traditional departmental PhD program. The key is interdisciplinarity, and to be successful one must be able to communicate across discipline boundaries. While the IGERT faculty representing such diverse research efforts already offers a vibrant intellectual environment that spans many science and engineering departments, the IGERT program is greatly needed in order to provide the kind of PhD support not available from individual grants, but vitally important to initiating, stimulating and sustaining cross-disciplinary research. Numerical and experimental analysis of turbulent flow [PKY,DRW,PJM,EDL], experimental detection of signal transmission through fluid media [HY,JY], and information processing of images and signals acquired [KEK,EDL] by sensory arrays are all required and can be provided only by cross-disciplinary teams. Here the proposed IGERT will foster the necessary collaborations.

Experience from sister programs already demonstrates that IGERTs are very attractive to the best graduate students, as IGERT Fellows are given a great deal of independence in choosing co-advisers, and encouraged to take part in collaborative research projects nationally and internationally. This IGERT program will seed the infrastructure that should outlive the NSF grant, supporting the new research directions through workshops and visitors, both from other nonlinear science research centers, and from institutions which could potentially apply the IGERT fostered methodologies to outstanding challenges in other disciplines. At present, no framework provides such a meeting place for the advancement of our cross-disciplinary research goals.

In summary: The goal of research in dynamics in many dimensions is to stimulate development of novel methods for characterizing and classifying spatiotemporal complexity. As the methods and approaches of nonlinear science are still relatively unknown in many areas where these methods have potential applications, the second long range goal of this IGERT is to transfer the new tools of nonlinear science to important problems arising from advances in technology and biology.

This IGERT program will address the grand challenge of nonlinear science: Explore experimentally and describe theoretically the dynamics of high-dimensional nonlinear, noisy systems. Furthermore, this IGERT will foster applications of the methods thus developed to problems in engineering and biosciences.

d. Education and Training

i. Overview

In order to produce highly capable graduates who can eventually lead in the complex research challenges detailed above, we envision a comprehensive training program which cuts across ten academic units and includes coursework, research, seminars, mentoring opportunities, national and international internship experiences, each described further below. *Integrating these five components in a truly interdisciplinary context will help promote a cultural shift in graduate student education, of the type crucial for maintaining US leadership in both the physical and natural sciences.*

Students will be recruited with competitive IGERT Fellowships to study in any of the participating departments. Each Fellow will be enrolled in their home department's PhD degree program, and at the same time will pursue a structured minor in Nonlinear Science. GT has a well-established tradition in interdisciplinary research collaborations and degree programs, frequently including doctoral theses with co-advisors from different departments. The IGERT program will build on this experience.

A **Welcoming Workshop Retreat**, early in the fall semester, will introduce incoming IGERT Fellows to the program. An overview of the IGERT program will be provided by the program Director followed by brief presentations by the IGERT faculty to familiarize Fellows with various research programs. Presentations will also be given by senior graduate students on their work in the project-based course (to be described later), during their internships or their thesis research. The informal part of the retreat will feature smaller group meetings where senior students can share their experiences with the incoming students and the incoming students can explore advisement possibilities with faculty. These interactions will facilitate the placement of each student with a Nonlinear Science advisor outside the Fellow's home department.

The Nonlinear Science advisor will work together with the Fellow's academic advisor in the home department, to make sure that the Fellow is adequately prepared for the program, particularly the subject areas outside the Fellow's major. All IGERT Fellows are expected to fulfill academic requirements for a PhD in their home department and for a Nonlinear Science Certificate (or minor). This certificate will consist of four IGERT-related courses and fulfills an already existing GT requirement for a minor. A number of these IGERT courses already exist and have significant nonlinear science content, while others will be developed by interdisciplinary IGERT faculty teams, a plan supported by the respective School Chairs. These courses will be open to everyone and will benefit both IGERT Fellows and all students interested in nonlinear science. The courses comprising the IGERT training program are summarized below. (Note on the GT course numbers: level 4000 = senior undergraduate, 6000 = 1st year graduate, 7000 = 2nd year graduate, 8000 = advanced graduate)

ii. Interdisciplinary Coursework

Level 0: Methods of Mathematical Modeling and Analysis

Extensive experience in teaching nonlinear science at GT and elsewhere shows that students with biology and biomedical engineering backgrounds often lack some basic mathematical tools necessary for analytical and numerical studies of systems, even in their own discipline. A new course, *Mathematical Modeling in Biological Sciences*, will be developed to prepare such students for more advanced courses in Nonlinear Science described below. Drawing on experiences of existing courses (*Modeling and Dynamics* MATH 6705 and *Mathematical Biology* BIOL/MATH 4755), this course will assume only a modest background in mathematics, including single-variable differential calculus and vector calculus, and use case studies in discrete- and continuous-time population dynamics, kinetic equations, biophysical models of neurons, gene networks, and disease dynamics to introduce the basics of matrix theory, ordinary differential equations, deterministic dynamics, Markov processes, statistics, and numerical methods. Numerical solutions will be used extensively to develop students' intuition in relating the structure of the model equations to the properties of their solutions. (EV/BME, CAK/Bio, LAB/Math)

Level 1: Core Techniques of Nonlinear Science

In the Spring semester of the first year, all Fellows will take a formal lecture-based course on the mathematical and computational techniques of nonlinear science, *Introduction to Nonlinear Dynamics and Chaos (PHYS 4267/8803)*. The course, based on Strogatz's textbook "Nonlinear Dynamics and Chaos", has been taught for a number of years at the graduate/advanced-undergraduate level and attracted a wide range of students from Physics, Mathematics, Biology, Chemistry, Biomedical, Chemical, Civil, Mechanical and Aerospace Engineering.

The course assumes a basic knowledge of linear algebra, ordinary differential equations and numerical methods. Designed around numerous examples from physics, chemistry and biology, it provides a gentle introduction to the qualitative analysis of discrete- and continuous-time dynamical systems, stability of fixed points and limit cycles, bifurcations, universality, chaos and fractals. This course will familiarize IGERT Fellows with the basic concepts of nonlinear science, and establish a common language for bridging the disciplines and provide students with the foundation necessary for more advanced nonlinear science courses. (PC/Phys, RG/Phys)

Level 2: Cross-disciplinary Studies of Nonlinear Science

After learning basic concepts and techniques in Levels 0 and 1, IGERT Fellows will be expected to take at least two Nonlinear Science courses in an area outside their primary training (e.g., biology for students in mechanical or aerospace engineering, physics for biology students, etc.) in order to broaden their exposure to high-dimensional systems in other fields, and build the basis for future interdisciplinary research with their IGERT faculty co-advisors. The Center for Nonlinear Science maintains (and will expand as appropriate) a list of courses offered by various academic units, reflecting the breadth of subject expertise found in our diverse faculty team. Representative courses on this list include:

- *Exerimental Nonlinear Phenomena (new course)* The objective is to expose students to characteristic phenomena that exhibit nonlinearity, fluctuations and randomness. The students will be exposed to the relevant mathematical modeling (without going into details) and experimental visualization of the phenomena. These phenomena will be examples primarily taken from observations that are commonplace but evade the attention largely because they occur at high speeds. Examples will include fluid drops impinging on solid and liquid surfaces, breakup of fluid jets, dripping faucets, droplet coalescence or noncoalescence, rolling of drops on an inclined plane, cavitation (a la snapping shrimp), and other not-so- commonplace observations of the flicker phenomena of healthy red blood cells, fluctuations of a DNA chain moving through fixed obstacles and fluctuations of ordered fluids.

  This course will take place in the IGERT Laboratory that will be set up using the funds requested under this proposal. It will be used by other IGERT lab courses and the rest ot the time serve as a shared facility available to IGERT Fellows to pursue independent experimental projects at any time during the course of their graduate studies.

- *Spatiotemporal Dynamics and Pattern Formation (PHYS 7224).* The objective of this course is to develop a unified mathematical framework describing the dynamics and pattern formation in out-of-equilibrium dissipative systems, such as sand dunes, ocean waves, atmospheric convection, animal coat patterns, cell differentiation, contraction waves of the heart muscle and so on. This course addresses both specific and general aspects of pattern formation by deriving models of many common pattern forming systems, classifying solutions by symmetry, and analyzing their stability and bifurcations. Advanced topics cover nonlinear saturation and pattern selection, and the dynamics of weakly disordered patterns. Together with the new Stochastic Processes course described below, this course provides students with the basic mathematical tools for studying the dynamics of high-dimensional noisy systems. Prerequisites: basic knowledge of linear algebra, partial differential equations, and bifurcation theory at the level of PHYS 4267 (discussed above). (RG/Phys)

- *Stochastic Processes in Extended Systems (New course).* This course is a modified version of Phys 7123 (non-equilibrium statistical physics) and is suitable for advanced graduate students from the College of Science and the College of Engineering. The course consists of two parts: modeling of stochastic processes in non-equilibrium systems, and a survey of now-standard examples of emergent behavior in high dimensional systems. The emphasis is on conceptual frameworks, which are then illuminated by basic examples. Students explore these examples through hands-on computational exercises. Topics in the first part are random walks and flights, stochastic differential (Langevin) equations, and Fokker-Planck equations. Applications include first passage time problems, Kramers escape, enhanced fluctuations near bifurcations, and stochastic resonance. The second part covers mutual synchronization in nonlinear oscillator populations, cellular automata and self-organized criticality, highly-optimized tolerance, and basic pattern formation. (KW/Phys, PC/Phys)

- *Fluid Mechanics of Organisms (CEE 6263).* The objective of this course is to apply principles of fluid mechanics to the dynamics of biological organisms. Flows inside and around organisms are analyzed, and the effect of fluid mechanics on behavior and evolutionary trends are organized in fluid mechanics phenomenological categories, with emphasis on application to biological systems. Assignments include problem-solving exercises that draw applications from habitat and organisms flows. Additionally, students lead discussion of relevant research articles from journals such as *J. Exp. Biology*, *Nature*, *Science*, *Limnology and Oceanography*. The course is aimed both at engineering and physics students with limited biology background, and at biology and chemistry students with limited fluid mechanics background. (DRW/CEE)

- *Hydrodynamic Stability and Turbulence (CEE 6293).* The objective is to introduce flow instability and turbulence concepts that are important in all engineering and environmental flow applications. The course builds on fundamental fluid mechanics principles to address relevant environmental, oceanographic, and engineering applications. The course is divided into modules covering linear hydrodynamic stability analysis, chaotic mixing, and turbulence. In each module, the basic principles are introduced and applications to specific environment flow systems are discussed. The course assignments include a student project focusing on one of the emphasized topics. (DRW/CEE)

- *Theoretical Ecology (BIOL 4423/6423).* This class covers the theoretical underpinnings of ecology from populations to communities and ecosystems. Topics include: unstructured population dynamics in discrete- and continuous-time, age- and stage-structured populations, two-species interactions, community modules, biodiversity effects, models with spatial structure, non-equilibrium dynamics, community assembly, and nutrient-cycling. Students apply their newly acquired knowledge to independent modeling projects. This class would be an ideal course for students from other quantitative disciplines who want to contribute to ecology, because it introduces key ecological ideas in a mathematical framework. (CAK/Biol).

- *Biochemical Systems Analysis (New course).* The course introduces IGERT Fellows to the analysis of metabolic pathways, gene networks, and other regulated systems of relevance in biology, biotechnology and medicine. It briefly reviews traditional concepts of enzyme catalyzed reactions, compares alternative modeling approaches, and then discusses in detail modern methods of nonlinear biochemical systems analysis with algebraic and computational means. In particular, the course equips the students with techniques for the design of nonlinear pathway models, parameter estimation, analyses of steady states and stability, sensitivities and gains, numerical evaluations of transients, and phase-plane analysis. For complicated systems, the course discusses simulation methods for the assessment of biomedically relevant scenarios, such as environmental fluctuations or mutations, and generally of the effects of large perturbations on steady states and on the dynamics of transients and non-steady state attractors. The theoretical concepts are applied to case studies taken from the current literature. (EV/BME)

Other courses offered either in the Fall or the Spring of a given year which may be taken by IGERT Fellows to satisfy the minor in Nonlinear Science requirements will include: Turbulent Flow (AE 6012), Dynamics of Turbulence (AE 6080), Theoretical Ecology (BIOL 6422), Evolution (BIOL 6600), Aquatic Chemical Ecology (BIOL 6620), Biological Applications of Environmental Fluid Mechanics Laboratory (BIOL 6764), Advanced Cell Biology (BIOL 7010), Bioinformatics (BIOL 7023), Quantitative Electrophysiology (BMED 6787), Life Science - Cell Biology (BMED 8110/8111), Physiological Systems (BMED 8120/8121), Transport Phenomena (CHE 6200), Fluid Mechanics of Two-Phase Flow (CHE 6210), Statistical Mechanics of Liquids (CHEM 6481), Theoretical Chemistry of Polymers (CHEM 6755), Oceanography (EAS 6124), Inverse Methods in Earth and Atmospheric Sciences (EAS 6134), Geodynamics (EAS 6312), Introductory Fluid Dynamics and Synoptic Meteorology (EAS 6502), Atmospheric Boundary Layer Structure (EAS 6793), Dynamics and Bifurcations (MATH 4541), Mathematical Biology (MATH 4755), Ordinary Differential Equations (MATH 6307), Industrial Mathematics (MATH 6514), Special Functions (MATH 6584), Numerical Methods: Partial Differential Equations (MATH 6640), Numerical Methods for Dynamical Systems (MATH 6647), Biofluid Mechanics (ME4757), Introduction to Polymer Science and Engineering (ME 4777), Introduction to Fluid Mechanics (ME 6601), Hydrodynamic Stability (ME 7602), Mechanics of Polymer Solids and Fluids (ME 7771), Solidification Process (MSE 7420), Biophysics (PHYS 4802), and Renormalization Group Theory (PHYS 8803), and new PHYS courses in Classical Chaos and Quantum Chaos (from [25])

Level 3: Project-based Interdisciplinary Courses.

Offered in Spring semesters, this project-based course, made possible only if the proposed IGERT is funded, stresses communication skills, collaborative skills, and genuine cross-disciplinary research. The course will be more structured than an independent project would be, structured as separate sections with specific research projects carried out by small teams of Fellows supervised by pairs of faculty co-advisors teaching each section. The faculty will be selected for diversity of expertise and perspective, and will advise the Fellows and serve as examples of how an experienced researcher would approach each problem. The core of a typical project will be an intensive literature search and the identification of open research questions. Several such course sections that would be made possible by the IGERT funding, and the prospective faculty involved, include:

- *Multi-scale Physical-Biological Interactions in Oceans.* Student will study the response of aquatic organisms from small to large-scale fluid physical dynamics in the oceans using modeling and experiments combining biological and physical oceanography, fluid mechanics, and numerical simulation. Small groups of students (e.g., a biologist, engineer and mathematician) will work together to perform sensitivity analyses, theoretical considerations and experimental tests. (JY/Bio, PKY/AE, EDL/EAS, DRW/CEE, CK/Bio)

- *Brownian and Fickian Diffusion Simulations.* Students will develop Monte Carlo-based simulations of Brownian and Fickian diffusion of colloids and high molecular weight biomolecules under different flow conditions. Simulation results have a variety of applications. For example, an experimentalist can use results to study how diffusion affects the accuracy of micro- and nano-scale particle image velocimetry or molecular tagging velocimetry. Both of these are diagnostic techniques of current interest in micro- and nano-scale fluidics. Meanwhile, understanding the appropriate stochastic differential equations (SDEs) and simplifications thereof is of theoretical interest, while the accompanying computations can both introduce basics and explore advanced details of numerical solution of SDEs. (MY/ME, PJM/Math)

- *Understanding Turbulence Using Direct Numerical Simulations.* Students will adapt an existing post-processing code to extract detailed physical information from the extensive DNS database sets generated in the PKY and DRW research groups. Students will be encouraged to investigate various quantities and visualization from the data, and formulate their own research questions to be answered by the data analysis. (PKY/AE, DRW/CEE)

- *Effects of Microstructure in Macroscopic Properties of Materials.* Students will learn and utilize analytical and computational methods to explore the dependence of material properties on the material microstucture. Possible materials to be studied include composites, polycrystals and porous media. (GG/Math, KEK/CEE)

- *Pattern Formation, Selection, and Control.* Students will experimentally study pattern formation in several canonical fluid systems, including Rayleigh-Benard and Marangoni convection, and contact line instabilities in spreading films. Students will also learn to control the patterns using passive and active feedback control techniques. Theoretical foundations of control will be explored using a range of models, from very simple to physically realistic, these studies then guiding the experimental work. (RG/Phys, MFS/Phys)

- *Modeling Nonlinear Climate Dynamics.* The course will introduce the students to the various aspects of the climate system that are nonlinear, such as the abrupt climate changes reported in ice records, still unexplained. The students will focus on understanding and analyzing (through simple modeling experiments or using output from more sophisticated existing climate models) the complexity of the feedbacks of the ocean/atmosphere/ice/land/biologicals system under changing climate conditions. (EDL/EAS, PC/CNS)

iii. Interdisciplinary research, seminars, mentoring, and international collaborations

A **typical** IGERT Fellow course sequence is illustrated below, using an environmental science student and a physics student as an example. Students with insufficient mathematical background will additionally take the Level 0 course in the Fall semester of Year 1.i Typical departmental requirement for PhD candidates is seven core courses and four elective graduate-level courses to satisfy the major requirements, and at least three courses outside the department to satisfy the minor requirements. The course sequence for an IGERT Fellow whose major is environmental science would look like this:

Year 1 Fall: Earth System Modeling, Oceanography, Introduction to Climate Change, and Mathematical Methods of Physics I (or Mathematical Modeling in Biological Sciences). **Year 1 Spring**: Thermodynamics of Ocean and Atmosphere, Biological Oceanography, Inverse Methods and Time Series Analysis and Introduction to Nonlinear Dynamics and Chaos (minor). **Year 2 Fall**: Biogeochemical cycles, Introductory

Fluid Dynamics and Synoptic Meteorology, Theoretical Ecology (minor), Introduction to Fluid Mechanics (minor). **Year 2 Spring**: Introduction to Complex Environmental Systems, Remote Sensing of the Atmosphere and Oceans, Pattern Formation (minor) and Fluid Mechanics of Organism (minor). **Year 3 Fall**: Project-based Interdisciplinary IGERT course (minor), Thesis Research. **Year 3 Spring – Year 5 Spring**: Thesis Research.

For an IGERT Fellow whose major is physics, a typical course sequence would be:

Year 1 Fall: Classical Mechanics I (core), Quantum Mechanics I (core), Electricity and Magnetism I (core) and Mathematical Methods of Physics I (core). **Year 1 Spring**: Statistical Mechanics I (core), Quantum Mechanics II (core), Electricity and Magnetism II (core) and Introduction to Nonlinear Dynamics and Chaos (minor). **Year 2 Fall**: Mathematical Methods of Physics II (elective), Condensed Matter Physics I (elective), Stochastic Processes in Extended Systems (minor), Introduction to Fluid Mechanics (minor). **Year 2 Spring**: Renormalization Group Theory (elective), Condensed Matter Physics II (elective), Pattern Formation (minor) and Hydrodynamic Stability and Turbulence (minor). **Year 3 Fall**: Project-based Interdisciplinary IGERT Course (minor), Thesis Research. **Year 3 Spring – Year 5 Spring**: Thesis Research.

Thesis research is expected to become the major part of the training program for all IGERT Fellows by their third year (or earlier). Fellows will integrate expertise from several disciplines to solve problems at their interface, such as those topic areas described under Major Research Efforts [see Sec C.c]. Each Fellow is expected to fulfill all of the normal degree requirements of his/her home department, including Qualifying or Admission to Candidacy exams, thesis proposal and the final defense. Students will be encouraged to invite additional IGERT faculty members to serve on their thesis committee and thereby provide an interdisciplinary perspective, especially for the task of communicating research achievements to a broader audience.

In order to offer students a deep learning experience outside the PhD thesis research, the educational core of the training program will be supplemented by the IGERT Informal Research Seminar, the IGERT Profession & Ethics Seminar, the continuing Nonlinear Science Seminars, and research mentoring of undergraduates, each described below.

Our IGERT program will provide ample opportunities for learning and mastering important skills in oral and written communications. We will implement a bi-weekly **IGERT Informal Research Seminar** series where the speakers will include a mix of IGERT Fellows, Center for Nonlinear Science postdocs, IGERT faculty, and occasionally visiting researchers. With speakers drawn predominantly from local sources, this seminar will run with only minimal cost. All Fellows will be expected to attend this seminar on a regular basis, as it will inform students of the research activities taking place in the framework of the program and stimulate collaboration and initiation of new interdisciplinary research projects. Furthermore, this biweekly seminar will provide an informal setting for IGERT faculty and students to interact with one another in a way that promotes a sense of community. In the first year, IGERT's Assistant Director will be the primary seminar organizer, after which this task will gradually be passed on to advanced IGERT Fellows.

The **IGERT Profession & Ethics Seminar** series will be offered a semester long course to students in their 3rd year and will address such topics as professional advancement, ethics, participation of underrepresented groups, the environment, societal priorities, and public policy, all from an interdisciplinary scientific perspective. Possible sources of speakers will include, e.g., the *Sigma Xi*'s Visiting Lecturer program `www.sigmaxi.org`. The GT alumni previously associated with the IGERT faculty will be invited to discuss career options and their experience in industry, business and government. Such seminars were well received at U. Texas and U. Chicago and will provide graduate students with information on professional and societal dimensions of interdisciplinary research.

IGERT faculty & Fellows, in coordination with the *Executive Committee*, will invite external speakers including those who are leaders in their own field and can speak to broad audiences to speak in the weekly **Nonlinear Science Seminar** [29]. This seminar, initiated in January 2001, draws a wide attendance from across GT and other Atlanta institutions. The seminar has been financed to date by the CNS start-up funds provided by GT, which expire at the end of 2004. The funds requested under this proposal, supplemented by individual grants, will enable us to continue running the seminar for the duration of the IGERT program.

The scope of the seminar will be broadened to include more engineering and biological applications, making it truly interdisciplinary. IGERT Fellows will also invite speakers for this seminar and the Profession & Ethics seminar through their representative on the *Executive Committee*, with the stipulation that at least 2 external IGERT seminar speakers are selected and invited by the IGERT Fellows each semester.

In order to enhance the educational impact of this research seminar and to better integrate it into the interdisciplinary training program, Nonlinear Science Seminar speakers will be asked to give an informal, 15-minute introductory presentation prior to their official seminar. By separating this presentation from the main seminar it will be easier for the presenter to adjust the level of presentation to the level and background of the students. To facilitate further discussions among students, faculty members and the speaker, a coffee break will be held after the seminar. Additionally, to give students a better perspective and understanding of the diversity of job opportunities, the speaker pool will be drawn from academic and government institutions and industry.

While IGERT Fellows will undertake a wide variety of post-graduate careers, we expect a significant fraction of well-trained PhD students in this program to ultimately pursue a career in academia and hence play a significant role in educating the next generation of scientists and engineers. To help train our students in their role as future educators, we shall ensure that IGERT Fellows have at least one semester's teaching assistant experience in the course of their graduate training. We shall also arrange for advanced PhD students to act as informal research mentors to selected undergraduates. Fellows will have an option of gaining additional mentoring experience through our IGERT's high-school outreach effort [see Sec C.b].

The proposed IGERT educational plan will impose in the Fellows coursework and responsibilities beyond those required of single-department PhD students. Nevertheless, for the CoS Fellows the time to degree will be shortened, as they will be relieved from GTA obligations, and thus be able focus solely on study and research. CoE students are routinely not supported as GTAs: in their case the IGERT fellowships will allow them flexibility in broadening their backgrounds,and greater independence in structuring their research through choice of co-advisors.

A **visitor program** will help establish, promote and maintain national, international, and industrial collaborations, with priority given to visitors who demonstrate potential as external mentors to IGERT Fellows. The length of the visit in each instance will be chosen commensurate with the time required to identify and initiate a new collaborative research project. Longer visits will also be possible in cases where external funding from the visitor's host institution is available.

While the nationally highly ranked IGERT faculty has broad expertise across several branches of nonlinear science, some of the research projects will require expertise and/or collaborations not available locally within GT. With a relatively small number of high level nonlinear programs in the US, the international collaborations are essential to maintaining US research on high-dimensional nonlinear systems at the cutting edge. Much of the cross-disciplinary research at GT already has a significant international component. These well established connections will be used to provide the Fellows with internship experiences at one of the sister centers [see Sec C.i].

IGERT internships will offer the Fellows participation in collaborative cross-disciplinary research at the highest level, international and national. In conducting research, the flux of ideas across disciplinary boundaries is most effectively nurtured through a cross-disciplinary training program which integrates research, education, and training. In cases where the thesis research warrants it, IGERT will sponsor semester-long Fellow internships at international or national nonlinear science sister centers [30, 31], and will in return host interns sent to GT by sister centers. Internships will, on the one hand, offer the Fellows invaluable expertise needed in their research and, on the other hand, bring into IGERT foreign interns (at their home institution's expense), thus enhancing the quality of the IGERT Fellows' research environment.

An annual one-day **IGERT Southeast Nonlinear Science Workshop** will be organized jointly with other Southeastern universities or national laboratories, such as Duke, Univ. of Alabama, Univ. of Florida and Oak Ridge National Lab. As an important IGERT training component, the workshop will be oriented primarily towards students from regional universities. The main goals are to expose students to the cutting edge research, give them a platform to present their own work, and build experiences in organizing and participating in professional activities. For these purposes, the main body of the organizing committee will be composed from senior graduate students and junior faculty members with students accepting lead roles and faculty available for advice. The workshop will have a broad scope, covering different branches of nonlinear science in different disciplines. This broad scope will give students a sense of diversity and at the same time closeness of the nonlinear science community, highlighting many existing and prospective links between different directions pursued by different research groups. The workshop will include the following activities: approximately six speakers, majority being graduate students and junior faculty from regional universities, will showcase their recent interesting research results. Two world leading external researchers will be invited to give overviews on recent important developments in the nonlinear science in their disciplines. Also there will be a poster session for participants to display and discuss their recent progress in research. Additionally, a panel discussion will be held at the end of the workshop. Senior faculty members will be on the panel to address the prospectives of nonlinear science and future research directions, and answer questions raised by students.

Nonlinear Science Summer School, a summer school program will be hosted by the IGERT in conjunction with the CNS and one of the sister international centers (refer to the sister center list) once every two years. In contrast to the IGERT Southeast regional nonlinear workshop, the summer school is an intensive learning opportunity to prepare IGERT Fellows and students from other participating institutions for the research level knowledge in nonlinear sciences. The two-week school will have about six international leading experts giving sequences of tutorial-style lectures. The topics will cover established fronts in different branches in nonlinear science. For instance, IGERT proposes to co-host a summer school in the "Stochastic and high-dimensional nonlinear processes", either in Atlanta or at the Centro International de Ciencias, Cuernavaca, Mexico [30]. In addition, about six national an international researchers will be invited to give colloquium-style presentations on the cutting-edge forefront in nonlinear science.

As their research progresses, all IGERT Fellows are expected to present their research at national or international conferences, and eventually to publish their work in appropriate scholarly journals. IGERT funds will be available to support such conference travel and (if necessary) journal publication page charges. Publications and presentations in inter- or cross-disciplinary outlets will be especially encouraged, and will be used in the later stages of our project as one of several assessment metrics for our degree of success at interdisciplinary education and training.

e. Organization, Management, and Institutional Commitment

The *Director* of the proposed IGERT program is P. Cvitanović (School of Physics), who holds the Glen Robinson Chair in Nonlinear Sciences and is the director of GT Center for Nonlinear Science. In the period 1993-1998 PC founded and directed the *Center for Chaos and Turbulence Studies* at the Niels Bohr Institute, Copenhagen [PI's and Co-PI's administrative qualifications are detailed in Sec C.h]. In the proposed IGERT, PC will be assisted in the academic program and administrative management functions by the *Assistant Director* Raenell Soller, the *Executive Committee* of four faculty with expertise stretching across the GT disciplinary boundaries, and an IGERT Fellow. The initial *Executive Committee* will be LAB, KW, PKY and JY, the proposal co-PIs. JY and PKY will also serve as the IGERT deputy-directors for the Colleges of Sciences and Engineering, respectively. The student representative will be elected at the beginning of each Fall Semester by the IGERT Fellows.

The Executive Committee will meet at least monthly during the Fall and Spring semesters, and will be responsible for administering the award of IGERT fellowships, visitor invitations, international exchanges, and for managing IGERT budgetary resources in accordance with the goals of the program. In particular, the committee will develop and execute a formal mechanism for awarding IGERT fellowships based on the quality and cross-cutting impact of a short proposal jointly developed by a student and two or more IGERT faculty. With emphasis on interdisciplinary activity, the estimated cross-cutting impact of the short proposal will include whether the selected IGERT faculty are from different academic units, but will be made without regard for faculty status (e.g., being PI or co-PI, or academic rank). The Committee will actively solicit input from IGERT Fellows, IGERT faculty, and from the Advisory Board [see Sec C.f below]. The *External Advisory Board* shall consist of three nationally recognized experts in nonlinear science, each of whom shall visit GT individually once a year, and who together will visit GT for the mid-term program assessment.

The institutional environment at GT strongly encourages interdisciplinary activity. There are numerous Research Centers on campus and three currently funded NSF IGERT programs that receive substantial GT cost-sharing and assistance.

We have received commitments of institutional support including cost-sharing at three different administrative levels:

- The Chairs of the ten Schools (units which termed departments at other universities are labeled "Schools" at GT) have expressed their strong support for participation in this proposal. Each School is committed to (a) a year of regular Ph.D. assistantships support in addition to each IGERT Fellow's 2-year fellowship;(b) having the School graduate coordinator work with the IGERT administration to recruit IGERT candidates; (c) designating a portion of faculty teaching load to courses related to this IGERT; and (d) supporting faculty initiatives to develop new courses and further supporting the incorporation of these courses into the GT curriculum beyond the duration of the IGERT.
- The Vice-Provost for Research and Graduate studies (C. Liotta) has committed to providing 80% support for the Assistant Director in Years 2-5 of the proposal. Moreover, the Vice-Provost has committed $40,000 in seed funding earmarked for IGERT Fellows who submit proposal requests for research funding. (These proposals will be evaluated and selected in a competitive process.) A supporting letter from the Vice-Provost is attached.

The faculty involved in this proposal have close ties with leading researchers who are in senior positions at a number of institutions and major research centers abroad. As discussed in Sec. C.i several of these have agreed to collaborate with us, visit us for extended periods, and/or host our students for 3-6 month periods.

f. Performance Assessment

We shall implement a detailed assessment plan aimed at evaluating our progress in promoting interdisciplinary research and education in Nonlinear Science, including considerations for human resource development. In preparing our assessment plan we have drawn upon the experiences of PIs of related IGERT, VIGRE and other grants [detailed in Sec C.h]. The Office of Assessment at GT has committed to assist us in soliciting (anonymously if appropriate) feedback from students, faculty, internship hosts and visitors involved in our program. The IGERT Assistant Director will continously track data on objective measures such as enrollment level in Nonlinear Science courses, time-to-degree for PhD students, research publication activity, statistics on recruitment, retention, and participation by underrepresented groups. These findings will be examined by the Executive Committee and presented to the Advisory Board, annually, for the 3. year reviews, and for the NSF 5th year review. The running assessment data will be used to for mid-course IGERT program improvements:

1. **Training.** We will track the number and performance of students taking the IGERT interdisciplinary sequence. Each IGERT Fellow will receive an annual review from the Executive Committee, noting the progress towards the degree. If enrollment levels are low we will improve advertising and adjust the IGERT curriculum to match more closely with student and program needs. If insufficient interdisciplinary background is a concern in limiting student achievement, the instructors will provide expanded coverage of basic prerequisites both in class and through additional tutorial sessions. Student feedback in course evaluations managed by the GT Center for Enhancement of Teaching and Learning will be carefully considered.
2. **Research.** We will look for evidence of interdisciplinary research contributions, including publications by faculty and students in interdisciplinary journals and presentations at interdisciplinary professional conferences.

   We will use the assessment data to identify areas where interdisciplinary collaborations encounter difficulties and direct the IGERT resources to meeting specific needs, e.g. by seminars and workshops aimed at promoting collaborative efforts between different research communities.

3. **Diversity.** We will monitor the number of IGERT students belonging to underrepresented groups and compare their academic and research performance with that of other students. We will work with the GT Women in Science and Technology Office, the Office of Minority Education and Development, and the Office of Assistant Dean of Students for Disabilities. We will also monitor the size of the recruitment pool which is likely to be small compared to the general student population.

   We will strive to maintain a focus on the quality of students and not just mere collection and analysis of numbers. The issue of diversity is challenged by the need to define quantities to measure quality. The goal and overall spirit of diversity needs to always be a central vision for all faculty and students. Once quantities become more important than quality, progress can become stagnant. Quantities are needed for proper assessment of goals, but guidelines need to remain flexible rather than set quotas. Problems evolve when goals are met, but attitudes do not change. Genuine interest in creating a diverse environment for research and learning is essential to actually obtaining that diversity. A person with oversight and influence needs to reassess goals to ensure that students are viewed as individuals with talent, intellect, and the ability to contribute to society, rather than a number that satisfies quotas or NSF guidelines. Goals will require redefining until diversity has become the norm and everyone believes that diversity benefits all.

4. **The External Advisory Board** will carry out functions of external assessment and provide recommendations for continual improvements to our program. All of the Advisory Board members will have deep experience in science and/or engineering management. At least one will be a PI or Co-PI from one of the earlier IGERT programs of a similar scope, so that s/he would have a broad perspective in evaluating the relative success of the current program. We view as crucial comments and recommendations from the Advisory Board and from our international partners about the students that they host.

g. Recruitment, Mentoring, and Retention

Our goal for recruitment and retention is to enroll and graduate a diverse student population, who are well prepared to succeed in an interdisciplinary scientific career and become future leaders for the scientific community. To achieve this goal, we will (1) implement an aggressive recruitment campaign at both the undergraduate and graduate levels (2) after recruitment, help the IGERT fellows to develop the long-term mentoring network critical to their professional success; (3) teach professional and personal skills that sustain individuals throughout their scientific career, and (4) develop a learning environment that welcomes and supports diversity. These efforts will maximize the impact of our IGERT training program.

Recruitment Campaign. Our IGERT program will work closely with the ten affiliated graduate schools. The PhD programs in which the IGERT graduate students may enroll are Aerospace Engineering, Biology, Biomedical Engineering, Chemistry and Biochemistry, Civil and Environmental Engineering, Earth and Atmospheric Sciences, Mathematics, Mechanical Engineering, Physics and Polymer, Textile and Fiber Engineering. We will work closely with these graduate programs during their application and admissions cycle. All School Chairs have agreed to support our recruitment efforts.

We propose to recruit five new PhD students to the IGERT program each year, with fellowship offers that cover the first three years of graduate study. Experience with recruiting graduate students to our individual departments indicates that multiple-year fellowship offers are extremely attractive to prospective students. Such fellowships give students freedom to focus on their studies and to also choose their thesis topic and research advisors with less concern about funding. The fellowship offer combines two years of IGERT funding with one year of school support. The Chairs of all participating Schools have signed a letter committing an additional year of graduate support for any IGERT fellows within their department in the form of a GRA or GTA. By combining resources, we will be able to offer fellowships with competitive stipends, as well as provide continuation funding to more senior IGERT graduate students who have already started cross-disciplinary thesis research.

We expect that students who are eligible for IGERT fellowships will also be strong candidates for internal awards such as the Presidential Fellowship (PF), which offers an annual stipend of $5000. Fellows from underrepresented groups will also be eligible for the Goizueta Fellowship (Hispanic), President's Minority Research Fellowships, and Patricia Roberts Harris Fellowship (women and minorities). These internal awards will be used when possible to supplement the GRA and GTA offers in effort to allow students to maintain a consistent level of financial support during their graduate career.

IGERT applicants will consist of both graduating seniors and current graduate students. We will survey the academic background and interest of all eligible persons who have applied to one of our qualifying graduate programs in order to build our candidate pool. We will also recruit students from our existing pool of first- and second-year graduate students who are enrolled at Georgia Tech. When selecting Fellows, we will favor students with strong academic records and previous research experience who also show interest in cross-disciplinary research and societal commitment.

To publicize the many opportunities available to potential IGERT fellows, we will widely advertise our program nationwide, with special efforts to attract the best and brightest members of underrepresented groups (URG), i.e., women, African-Americans, Hispanics, Native Americans and people with disabilities. Mailings, faculty visits, and faculty contacts will be the primary venues for publicity. Once a year we will send out mailings to the Graduate Advisors of the top 25 undergraduate feeder departments nationwide. The mailing will include a brochure and poster with comprehensive information about our Training Program. These brochures will also be distributed to African-American, American-Indian, Women, Visually-Impaired and Hearing-Impaired Colleges and Universities. Examples of these institutions are Morehouse, Oglala Lakota, Wellesley, Royal National College for the Blind, and National Technical Institute for the Deaf (associated with Rochester Institute of Technology), respectively. Additionally, since the majority of students from underrepresented groups are enrolled in mainstream colleges, we will also target the top 10 universities in terms of Hispanic and African-American enrollment. Furthermore, we will distribute our mailings to the Disability and Minority Development Offices at our top selected 25 feeder institutions. These offices have personal interactions with the students they serve. For example, Georgia Tech's ADAPTS (Access Disabled Program for Tech Students) director, Assistant Dean of Students Denise Johnson, has already agreed to identify undergraduate GT students who are receiving majors in a relevant field and send them information about our program. We will also advertise our program via a well-maintained IGERT website and through IGERT links on the web sites of participating Schools.

All IGERT faculty will contact their colleagues at various universities and inform them about our training program. This is essential to our recruitment effort; an NSF survey of existing IGERT students nationwide found that the majority of students learned about the IGERT program through a faculty advisor or a related undergraduate experience. These contacts require minimal time commitment but are integral to a successful recruitment program.

Recruitment of graduate students already at GT will focus on increasing the on-campus visibility of our program. IGERT faculty, brochures and posters will be used to advertise the program in all participating Schools. The IGERT-related courses will be open to all students on campus, and will therefore also be used to publicize this program to current GT graduate students.

Develop long-term mentoring network. Once the students are recruited, we will focus on a retention program that supports their educational and professional careers. Research has shown that persistence and academic success have as much to do with social interactions and social adjustments in the college setting as do variables such as socioeconomic background and academic preparedness. [44] Investments in 'social capital' will prevent members of URG, who are of equal or better 'human capital' (their skills and knowledge), from withdrawing from graduate school. Thus, integrating our students socially into our program becomes a main priority in the retention process.

A program that establishes mentoring relationships that begin the summer before students arrive on campus and continue throughout the student's graduate education will facilitate student retention. Mentoring is extremely important for URG students, since these individuals often feel isolated and different within a scientific community. These feelings prevent students from developing their personality and creativity, and thus successful research. A well-structured mentoring program will help them avoid isolation by providing them with peers, teachers and role models. A peer mentor will be assigned to each student prior to her/his arrival at GT, so the student can have a contact concerning housing and other graduate life issues. Next, IGERT fellows will join current students and faculty at a one-day retreat held at the start of each fall semester. The new students will pair up with a nonlinear science advisor, who will oversee the student's progress during the first two years in tandem with the departmental advisor. This mentoring program will provide every IGERT fellow with one peer mentor and two faculty advisors.

Given time constraints and demands on faculty, our IGERT Assistant Director will track mentoring and advising relationships. She will meet once a semester with each IGERT fellow to discuss mentoring/advising relationships and any other needs of the student. Because we desire to pair URG students with a peer or faculty mentor who is an URG scientist her/himself, we will focus on identifying faculty mentors in the Atlanta area who are of ethnic backgrounds absent from our IGERT faculty; these individuals will also be invited to our welcoming retreat. Also during this welcoming retreat students will be formally introduced to support organizations such as the Black Graduate Student Association, Office of Multicultural Affairs, the GT Office of Minority Development and the Women's Resource Center.

In addition to providing students with mentoring and advising relationships, we will work towards developing a sense of community amongst our students. Towards this goal, the educational component of our program emphasizes cooperative projects during courses and also offers group seminars and workshops.

Teach professional and personal skills that will sustain individuals throughout their scientific career. Our IGERT program will foster and teach leadership, communication, creativity, scientific knowledge, interdisciplinary research, networking, and the ability to work in diverse teams. These skills will offer students the confidence that their graduate education is preparing them for a successful career. With this confidence, students feel committed to completing their graduate program and contribute towards our retention efforts. Leadership skills will be developed from student organized seminars, workshops, and student representation on the IGERT executive committee. Communication skills will be taught in the Profession & Ethics Seminar, where students not only develop written and presentation skills but also learn about positive methods for conflict resolution and negotiation. These latter skills are necessary for proper maneuvering through work-place dynamics; whereas, written and presentation skills are essential when communicating science to colleagues and society in general. Creativity, scientific knowledge, and interdisciplinary research will be emphasized during IGERT coursework and thesis research. Networking will occur through interaction with seminar speakers, visits with international IGERT faculty, and internship opportunities both domestic and abroad. Lastly, the ability to work in diverse teams will occur as we recruit a diverse student population and offer fellows opportunities for teaching and research collaborations at URG institutions, such as our connections with Spelman College.

Develop a learning environment that welcomes and supports diversity. This supportive environment begins by acknowledging that individuals of both genders and all ethnic backgrounds positively contribute to the intellectual advancement of science and engineering. Including all persons of talent enhances the performance of scientific professions and allows for a more efficent use of resources. Betty Vetter, founder of the Commission on Professionals in Science and Technology, pointed out the waste engendered by persisting barriers that cut short scientific careers in which there has been considerable personal and public investment. [45] Removing barriers that impede women and minorities from successfully negotiating the critical transitions of professional careers is a top priority for maintaining scientific excellence. Efforts directed towards accomplishing these larger societal impact goals will enable the development of an IGERT learning environment that welcomes and supports diversity. This will provide students of all backgrounds equal opportunities for success in scientific careers. In addition to the recruitment and mentoring activities already mentioned above, our efforts at supporting a diverse environment will focus on Faculty/Student forums that discuss diversity issues.

GT, as a leading educator of women and minority engineers at both the undergraduate and graduate levels, has many initiatives that focus on increasing women's and minorities' participation at the undergraduate levels (e.g., Women in Science and Technology (WiST), Women in Engineering, Women's Resource Center, and the Office of Minority and Educational Development). Furthermore, GT currently has a \$2M, 5 year NSF ADVANCE grant to bring about institutional change by increasing the number of female faculty. Programs focusing specifically on URG *graduate* students, however, require further emphasis.

Initially our efforts to incorporate diversity issues into our IGERT program will focus on a monthly

Graduate Women's Seminar, since they constitute half of the available talent pool. Participation in this seminar will be voluntary and open to all female students within participating IGERT Schools. The aim of this seminar series is to offer women graduate students support during their doctoral research, provide them with an informal setting to discuss issues unique to their experiences as women, and also encourage them to pursue scientific careers where they will become future role models. This Seminar will bring together female graduate students from Earth and Atmospheric Sciences, Physics, Biology, Mechanical Engineering, and other departments for a luncheon where students give brief presentations on their research. The goal is to provide a friendly, nurturing environment for women students to develop their skills as seminar speakers and facilitate discussions on scientific topics that have drawn their attention. This format will create an interdisciplinary environment that exposes participants to a variety of topics and techniques in current scientific research. At the conclusion of the research portion of the seminar, students will network and discuss various professional issues encountered by women in science and engineering.

Seminar activities will be coordinated by an IGERT Fellow and faculty member, and a new team of coordinators will be appointed every year. Also, as recommended by the College Deans, we have developed connections with WiST and ADVANCE to coordinate efforts and combine resources to develop this seminar sub-series.

A *Graduate Minorities' Seminar* will then be established a few years later modeled upon the Women's Seminars. The Minorities' Seminar, will focus on bringing together African-Americans, Hispanics, Native Americans and students with disabilities.

Our GT IGERT faculty consists of 5 women and 20 men, 1 Hispanic, 7 Asians and 18 Caucasians with one faculty member who is hearing-impaired. Given the limited racial diversity of our faculty, we will encourage faculty to support cultural diversity by offering a training session directed by GT's Office of Diversity Management at the welcoming retreat. Also as collaborations continue with Spelman, Morehouse and Clark Atlanta, faculty will gain exposure to African-American and Women culture. To ensure that the students can express their concerns regarding faculty behaviors that may seem unfriendly to URGs, all the fellows will be informed at the welcoming retreat and during the Women's and Minority Seminars that they can address their concerns confidentially with the Assistant Director, the Executive Committee, or the Dean of Students.

h. Recent Traineeship Experience and Results from Prior NSF Support

Individually, the IGERT faculty members already have extensive graduate training records. Here, we highlight our experiences with several prior or current NSF training grants, and one Danish Natural Sciences Research Council grant that are relevant antecedents to programs of our proposed IGERT's scope. In the period 1997-2000, prior to moving to GT, P. Cvitanović led the initiative to create a Center for Complex Systems at the Northwestern University, and was the original PI on the **IGERT #9987577**: *Complex Systems in Science and Engineering program* [46], awarded to Northwestern for the period 2001-2005. Though not involved in running this IGERT (ably led by H. Riecke), PC was instrumental in assembling the cross-disciplinary team which formed its basis, and has followed closely program's activities through its 5 years.

This IGERT proposal integrates the experiences of the Northwestern IGERT, as well as the thematically related Arizona and Cornell IGERTs, all three very successful programs. In particular, we draw upon Northwestern experiences in administering the internships, and the Arizona experiences in establishing the IGERT Biological Physics Teaching Laboratory. The student satisfaction is high, with the IGERT students benefiting substantially by the support from the grant, by the shorter time-to-finish, and by the recognition that it provides. For faculty, IGERTs are an invaluable resource in breaking down departmental walls.

PC has considerable experience in running cross-disciplinary programs of our proposed IGERT's scope. He co-founded and directed (1993-1998) the *Center for Chaos and Turbulence Studies* (CATS) [32] at the Niels Bohr Institute, Copenhagen, a successful cross-disciplinary effort which has evolved to be one of Europe's leading centers for nonlinear science, with approximately 15 faculty, 8 post-docs, 45 graduate students, 15 long term visitors, 40 short term visitors, and 5 workshops/conferences in any given year. The synergy of this "Copenhagen School" formed by particle physicists, nuclear physicists, condensed matter experimentalists and mathematicians, has led to a number of important advances. The core team continues the work to this day through the `ChaosBook.org` collaboration, a hyperlinked web-based course [25] which the proposed IGERT would develop further as an outreach effort. Today CATS continues within the *Complexity Lab*, directed by M.H. Jensen, one of the international institutional partners of the proposed IGERT (see the appended letter of intent).

European PhD programs typically require that their students spend 3-12 months abroad, with support from their home institutions; IGERT funding for Fellows visiting our European partners would enable us, in return, to host (and, in long run, recruit) students of such preeminent institutions as the French École Normale Superieure. As a former Secretary of European Dynamics Days Governing Board, PC has close working relations with the leading nonlinear science centers in Europe and elsewhere. Foreign interns hosted so far have been of significant benefit both to PC's research program, as well as to US students who interacted with the interns. IGERT will provide a framework for enhancing these student exchanges.

L.A. Bunimovich was co-PI and the Director of **GIG #9632032**: *Southeast Applied Analysis Center* (SAAC), based in the GT School of Mathematics, awarded for the period 1996-2002. Several outreach activities of this proposal build upon the initiatives pioneered by and contacts established by SAAC [33]. The goal of SAAC was to stimulate real life applications of applied mathematics and provide support to regional non-research and historically black universities in the Southeast. One highly successful SAAC program were the *SAAC ambassadors*, who delivered lectures on various forefront topics of modern mathematics in these universities and colleges, greatly appreciated by the faculty and students. SAAC has also contributed significantly to establishing the GT MS program in Bioinformatics, by developing new courses, through the SAAC seminar in Bioinformatics and Mathematical Biology, and by providing support to bi-annual International conference "Gene Discovery in Silico" which at the time was considered to be one of the best meetings in this area. Another highly successful SAAC activity was running annual "Southeast Probability Days", a meeting that regularly gathers about forty active probabilists and statisticians from the Southeast. As a part of its diversity recruitment effort, this IGERT intends to build upon this program by offering lecturers in mathematics, natural sciences and engineering.

Two of our IGERT faculty (D.R. Webster and J. Yen) have had valuable experiences from being on the team of the GT **IGERT #0114400**: *Signals in the Sea* (2001-2006) whose focus is biology, marine ecology, and environmental engineering. A key lesson learned is the importance of making sure that interdisciplinary courses are designed suitably for students from varied disciplines, most of whom have not had all the prerequisites needed. For example, biology students are not equipped with sufficient knowledge of mathematics needed for fluid mechanics courses taken by typical engineering students. In this case, the course development IGERT program grant made it possible for DRW to design an entirely new course (CEE 6263 Fluid Mechanics of Organisms, see Sec C.d.ii). The course was a great success as a truly interdisciplinary offering: with a roughly 50-50 split between biology and engineering students, it saw no great imbalance in the final grade distribution. Another success of the GT *Signals in the Sea* IGERT that we intend to build upon is their innovative Ethics Seminar.

With respect to the valuable past experiences described above, we can identify several **value-added aspects of the proposed IGERT project**, such as:

- *New areas of research.* Our proposal involves faculty members from 10 different departments across sciences and engineering, and is thus broader in its interdisciplinary content than most previous programs. It is a greater challenge, too, to provide students from such varied academic majors with training in a common set of methods, in this case the mathematical techniques of nonlinear science which have traditionally been developed by physicists and applied mathematicians. This IGERT will allow a fertile interchange among theoreticians, experimentalists, engineers and biological/biomedical scientists.
- *New educational paradigms.* As described in Sec C.d, a number of new courses with interdisciplinary themes will be developed, in each case bearing in mind the lessons learned from previous IGERTs, such as the CEE 6263 course mentioned above. A number of the proposed courses will be project-oriented and interdisciplinary, with the research supervised by pairs of IGERT instructors from different fields. The IGERT funding is here the essential prerequisite for creating the institutional setting and the

student demand necessary for such developments to take place.

- *Enhancement of training for all students.* The IGERT supports a small cohort of IGERT eligible graduate students, enabling the Fellows to typically cut one year off of their time to degree. However, the IGERT graduate student funding immediately widens the pool of students of all nationalities that are receiving support, thus leading both to a more vibrant interdisciplinary environment and increased levels of support for all graduate students.
- *Assessment, retention and under-represented groups.* As discussed in Sec C.f, in this grant we shall avail ourselves of the professional assistance of GT's Office of Assessment, well-staffed, able and willing to assist us in more rigorous fashion than previous related efforts at GT. One administrative innovation of the GT/Emory **IGERT #0333411**: *Hybrid Neural Microsystems* was inclusion of two Academic Professionals in its executive committee, one in charge of the graduate studies, and the other in charge of the diversity program. As we argue in Sec C.g, for a program as complex as ours, a full time Academic Professional (for which we seek partial NSF support) is critical in our task of mounting a rigorous effort at recruitment and retention. The particular diversity make-up of our IGERT faculty provides many prospective role-models for future IGERT fellows from under-represented groups.
- *National and international internships.* Our IGERT faculty take part in many international collaborations, and the appended letters of intent by the four distinguished, world-class scientists to host our IGERT Fellows are representative of a much bigger pool. These internships will be both a great educational experience for the young minds that we would like to train, as well as a strong recruiting tool for the IGERT program.

i. International Collaboration

The international aspect of the proposed program is crucial for advancing US to the forefront of research on high-dimensional stochastic systems. Currently the leadership positions in this field are often assumed by European and Japanese institutions. *The main international components of the proposed program are internships for IGERT fellows abroad, international workshops, and hosting senior visitors and interns from outside the US.*

IGERT fellows will be encouraged to complete a semester internship at one of the sister research centers, either within the US or abroad. The goal is to significantly broaden and strengthen the education of IGERT Fellows. This experience will provide young researchers with additional cross-disciplinary perspectives by exposing them to different experimental, computational, and theoretical approaches and by exposing them to expertise not available at GT. For example, a trainee working on theoretical projects in the home institution might intern in an experimental lab in a host institute or vice versa. In other cases, the internship would provide a specific experimental technique or theoretical approach not readily available at the home institution, but important for the trainee's thesis research. In addition, the internship program will play an instrumental role in forging new collaborations and identifying new areas of research opportunity. It is expected that the internship program for IGERT Fellows will be completely supported by the funds provided by IGERT.

The trainee, aided by the home institution advisor, will make the initial contact with a potential internship advisor. This contact will be facilitated by the existing long-term working relationships of the majority of IGERT faculty with researchers in leading foreign scientific centers. A brief proposal will then be written that clearly states the goals of the internship. The internship is expected to last one full Fall or Spring GT semester and is intended to form the basis for at least one publication. In exceptional cases where the extention of the duration of internship has a clear potential for significant progress, an extention for another semester may be granted after a review by the IGERT Executive Committee and home institution advisors. Upon returning to the home institution, the trainee will present her/his results in the Graduate Seminar Series and in the form of a written report which will form the foundation for a publication.

It is expected that (at least in some cases) scientific advisors will visit the host institution for a short period of time and provide guidance, with input form the local hosts, to interns. Such visits will typically be funded by the advisors' individual grants. Similarly, the faculty and students from the host institutions will be able to visit GT for periods ranging from a few days to several months to share their expertise, identify areas of opportunity or learn the tools and techniques developed at GT. Although such visits will be supported by the host institutions and/or IGERT faculty's individual grants, they will greatly enrich the scientific atmosphere of the IGERT program.

We further propose that a number of international workshops be co-organized by the IGERT faculty who already have a lot of experience in organizing international conferences, workshops, and symposia at GT. Some examples include Dynamics Days, International conferences in Mathematical Physics and Partial Differential Equations. Several faculty members were part of organizing committees of international conferences in US and overseas. The majority of IGERT faculty have international partner networks - sometimes quite extensive. For example, P. Cvitanović has organized and co-organized since 1981 about thirty conferences, workshops and schools in Europe and the US. The planned international workshops will either be devoted to emerging areas of nonlinear science or will be interdisciplinary, reflecting the broad research interests of the IGERT faculty. Not all such workshops will be held at GT (and even in US). Several IGERT faculty members have been approached by the directors of several international centers/institutes abroad to co-organize international workshops there. Such meetings will complement the more standard program of training and educating IGERT Fellows, providing additional motivation and expanding their horizons.

Internationally, some fifteen Sister Nonlinear Centers located in Argentina, Austria, Chile, Denmark, Germany, Hungary, Israel, Italy, Mexico, Netherlands and United Kingdom [30] are potential IGERT partners in organizing workshops, exchanging researchers, and hosting interns. The NSF IGERT rules (4 supporting letters, 4 international faculty, 2 pages) does not allow us to fully describe *the strength of already existing international collaborations and networks of IGERT faculty at GT, so here we provide just a few illustrative examples:*

International Center of Theoretical Physics (ICTP), Trieste, Italy (Director Prof. Sreenivasan) is one of the major and the largest international centers in theoretical physics. ICTP is a venue for many international meetings, including the biannual Summer School in Dynamical Systems. ICTP hosts a large body of visitors and has several very strong and vibrant research groups. IGERT faculty have many common research interests with permanent faculty in ICTP. After the appointment of Srinivasan as director, hydrodynamics became one of the focus research topics of ICTP. Many of IGERT faculty are working in this area (P.K. Yeung, P. Neitzel, M. Schatz, R. Grigoriev to name a few) and some already have working relations with ICTP.

Max-Planck Institute for the Physics of Complex Systems (MPI PKS), Dresden, Germany (Prof. Kantz, Head of Nonlinear dynamics and time series analysis group) is the main European meeting ground for young researchers and leading international scientists in physics of complex systems. The Institute hosts numerous workshops and is home to a well-known and extensive visitor, postdoctoral and exchange program. Currently, MPI PKS is establishing a PhD program where visitors such as IGERT interns will be even able to obtain formal credit (in US equivalent) for attending courses during their internship.

Complexity Lab, Copenhagen, Denmark (Director Prof. Jensen). Complexity Lab (formerly Center for Chaos and Turbulent Studies - CATS), housed at the Niels Bohr Institute, Danish Technical University and Nordita, is a leading European center in complex systems ranging from neuronal activity to quantum chaos. At any given time CATS hosts a number of interns funded by the European Union. CATS will also host IGERT researchers and interns. IGERT will host Danish Research Academy (a Danish PhD-granting School in Nonlinear Science)-supported students and visitors. As many European PhD programs require research training abroad, these and other similar exchanges will be very beneficial to the overall IGERT recruiting effort.

Institute for Advanced Biosciences (IAB), Keio University, Japan (Director Prof. Tomita). IAB, a leading world center in bioinformatics, computational, and systems biology. The scientists in IAB use ideas and methods of nonlinear science as major tools for modeling and simulations of the whole cell, analysis of gene networks, and study of protein interactions. Bioinformatics and bioengineering are main research efforts at GT, and many IGERT faculty are working in these areas. In addition to EV's present collaborations, it is fully expected that several other IGERT faculty will visit IAB to initiate fruitful collaborations and that IAB will become one of the central places for the IGERT internship program.

j. Recruitment and Retention History

GT has two internally funded fellowships for minority graduate students, the Presidential Minority Fellowship (part of the larger Presidential Fellowship Program), and the Goizueta Fellowship, for Hispanic Americans. These have helped GT maintain its position as the nation's leading producer of graduate degrees in engineering for African-Americans, as cited recently in *Black Issues in Higher Education*. GaTech is first in the nation in the number of engineering degrees awarded to African-Americans, second in the number awarded to Hispanics, and first in the number awarded to women.

The following pages give student data concerning admissions and degree conferral for the past three years. The data is broken down further by gender and race to give information regarding women and minorities. African-Americans, Hispanics and Native Americans are grouped together. GT complies with the American Disabilities Act of 1990 and is in a position to assist students with disabilities who enroll in our program to succeed in graduate school. Data tracking students with disabilities is not specifically recorded. The only data available is the number of students who voluntarily work with the Disabilities Office. There are only 4 students out of 4000 GT graduate students who utilize campus disability services. Three of these students are registered in one of our participating IGERT schools.

School of Aerospace Engineering (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	570	524	311	458	27	53	5.5
Women	68	59	30	54	1	9	5.7
Minorities	44	38	29	35	3	2	4.7

The School of Aerospace Engineering (AE) offers fully accreditated curricula leading to the degrees of Bachelor of Science in Aerospace Engineering, Master of Science in Aerospace Engineering, Master of Science (undesignated) and Doctor of Philosophy. Originally established in 1930 as the Daniel Guggenheim School of Aeronautics, the School has grown to be one of the largest in the nation, with 35 faculty members and a graduate enrollment which now stands at more than 400. Graduate students may specialize in areas including fluid mechanics, propulsion and combustion, structural mechanics, materials, controls, and multidisciplinary design of aeronautical and space vehicles. In recent years the School has initiated outreach programs such as videotaped offerings of selected courses of interest to industry and government, and study abroad programs in the summer where student participants gain international exposure in Russia,the United Kingdom and France. Faculty in the School have also played a leading role in the recent establishment of the National Institute of Aerospace, which is a multi-institutional consortium of education and research based at NASA Langley Research Center.

GT and its School of Aerospace Engineering offer one the nation's finest educational programs in engineering fields. Both the undergraduate and graduate programs in AE have consistently ranked among the top five. (Its undergraduate program has also produced two of the three prestigious Marshall Scholarship winners at GT in the last few years.) Currently we have one full-time faculty member each belonging to the three underrepresented groups of women, minorities and individuals with disabilities. With appointments pending, by Spring 2005 this number will change to 2 for both women and minorities.

The School of Biology (2002-2004)

	Applicants	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	134	119	61	78	21	12	5.4
Women	74	65	29	45	12	6	5.4
Minorities	9	8	0	5	1	1	4.3

The School is ideally suited for participation in the proposed IGERT program. Research in the department falls into four overlapping areas: 1) molecular and cellular biology, 2) microbiology, 3) ecology, evolution and behavior, and 4) bioinformatics. Particular research themes relevant to this IGERT proposal include the influence of turbulence on aquatic organisms (Yen) and the mathematical modeling of ecological systems (Klausmeier). The School has undergone tremendous change in the last five years. The faculty has doubled, including an almost complete overturn of faculty, and we have expanded from one building into three. This growth is reflected in a more than quadrupling of the publication rate from 1993 to 2003, and our expansion continues. This year the department hired a new department chair, Dr. John McDonald, whose vision of the department focuses on Systems Biology, an interdisciplinary, quantitative approach to biological systems into which this proposed IGERT program fits perfectly. The School is also the host of a successful existing IGERT program in Aquatic Chemical Ecology, which will provide further training possibilities and practical experience to this program, and participates in two interdisciplinary graduate programs in bioinformatics (masters and Ph.D). The School is also actively seeking other collaborative training and research programs with other disciplines, including an undergraduate training program in mathematics and biology. Recent graduates of this program have continued their training in postdoctoral positions at the Mayo Foundation, the Naval Research Laboratory, and the Pew Center on Global Climate Change.

Georgia Tech/Emory Biomedical Engineering Department (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	81	69	50	68	0	3	5.2
Women	39	34	26	42	0	1	5.7
Minorities	9	3	3	7	0	0	no degrees

The newest School in the College of Engineering, Biomedical Engineering (BME) was established in 1997 and has 30 primary faculty at present. Ranked second among graduate programs nationally by US News and World Report, the GT/Emory Wallace H. Coulter Department of Biomedical Engineering offers B.S. degrees in BME, M.S. and Ph.D. degrees in Bioengineering, all conferred by GT, and Ph.D. degrees in Biomedical Engineering conferred jointly by GT and Emory University. This unique partnership between public and private institutions is housed in the new $23 million, four-story, 90,000 ft2 U. A. Whitaker Building. Research activities in BME focus upon innovations in medical imaging, computer-assisted surgery, medical devices, and more efficient delivery of drugs to disease sites.

School of Chemistry and Biochemistry (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	189	180	157	236	9	59	5.3
Women	78	72	63	100	3	29	5.5
Minorities	22	21	17	28	0	?6	5.8

The School has an exemplary record of recruitment of exceptional students from around the nation. Over the past three years, the incoming Ph.D. class has increased from 37 to 48. The composition of recent classes is approximately 40The department has been successful in training these students as professional chemists and biochemists. The career tracks of alumni serve as a benchmark of the quality of the chemistry program as well as the ability to attract talented students. Georgia Tech Chemistry and Biochemistry alumni hold positions of responsibility in academe, industry, and government service. Numerous former students are tenured faculty members at colleges and universities across the country (e.g. Louisiana State University, University of Georgia, University of Central Florida, The Military Academy, Tennessee Tech, Appalachian State University, Kennesaw State University, Agnes Scott, Salem College, University of Tennessee-Chattanooga, Howard University, University of Central Arkansas, Westminster College, Tuskegee University, Florida A&M University, University of Richmond, University of Kentucky, and The Citadel). Other graduates have selected permanent staff positions in government research laboratories (e.g., NASA, Brookhaven, Oak Ridge, Lawrence Livermore, Argonne National Labs, NIST, Centers for Disease Control and Prevention). A particular strength of Georgia Tech is its interaction with industry. Chemistry Ph.D. graduates are heavily recruited and usually have numerous employment offers. Recent industrial employers of our students include: Georgia Pacific, Proctor and Gamble, Haliburton, IBM, DuPont, Celanese Acetate, 3M, Akzo Nobel Chemical, Ciba-Geigy, Milliken, and Zeneca).

School of Civil and Environmental Engineering (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	2015	845	259	305	31	66	4.8
Women	563	267	72	78	9	18	4.7
Minorities	91	50	22	12	1	5	4.6

The School of Civil and Environmental Engineering (CEE) offers courses in civil engineering, engineering science and mechanics, and engineering computer graphics, and programs leading to the degrees Bachelor of Civil Engineering, Master of Science in Civil Engineering, Master of Science in Engineering Science and Mechanics, Master of Science in Environmental Engineering, Master of Science (undesignated), and Doctor of Philosophy. The School is strongly focused on attracting and graduating women and minority engineers and scientists. A number of on-campus offices and programs facilitate the recruitment and retention of those students.

GT and CEE offer one of the nation's best graduate degrees in engineering fields. We offer one of the best combinations of quality, services, facilities, cost, and location. According to U.S. News: The Georgia Institute of Technology ranks # 5 nationally among graduate engineering schools. CEE ranks # 5 nationally in the field of Civil Engineering and # 9 in Environmental Engineering.

School of Earth and Atmospheric Sciences (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	362	89	58	81	8	17	5.8
Women	157	39	26	42	3	8	5.8
Minorities	45	12	11	10	1	2	6.0

The School of Earth and Atmospheric Sciences (EAS) prepares students for professional careers in environmental science and meteorology, and research careers in climate dynamics, atmospheric chemistry and air quality, oceanography, aqueous geochemistry and biogeochemistry, hydrology, geophysics and geohydrology. In addition to working in the new 261,000 sq ft Environmental Science and Technology Building, the School's faculty and students direct and participate in field experiments that span the globe from Atlanta, China, Nepal, Bangladesh, the Arctic Ocean, the South Pole and the remote islands of the South Pacific Ocean.

EAS has a total of 25 tenure track faculty, and an additional 28 research faculty. The EAS faculty have received considerable external recognition, and include two members of the National Academy of Sciences and one member of the National Academy of Engineering. Annual research expenditures in EAS exceed $8M.

School of Mathematics (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	433	102	50	70	6	19	5.6
Women	108	11	9	11	1	6	5.7
Minorities	18	2	3	2	0	4	5.2

The School of Mathematics has had a VIGRE grant for three years, which has been used to attract and retain 13 talented US citizens into the PhD Programs in Mathematics, as well as one in each of the two interdisciplinary PhD programs offered through Mathematics, Algorithms, Combinatorics, and Optimization (ACO), and Bioinformatics, which was launched in Fall, 2004. Several VIGRE Traineeships have also been awarded on a short-term basis to help other students in the program make more rapid progress towards their degrees. Also the fact that the School has been ranked by the American Mathematican Society has helped attract students from the top tier of college seniors in the last several years.

The School awarded two MS degrees to African-Americans in 2004. Since 2000, two PhDs have been awarded to US Minorities, as well as three to Subsaharan Africans and three to non-US Hispanics. In the same period, ten PhDs were awarded to women.

George W. Woodruff School of Mechanical Engineering (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	1844	1304	710	702	87	78	5.4
Women	165	98	53	52	15	13	5.4
Minorities	87	54	35	34	8	12	5.5

The School of Mechanical Engineering has 82 tenure-track faculty (all with Ph.D.'s), 21 research faculty, and five academic professionals. The faculty is divided into self-selected interest groups: Acoustics and Dynamics; Automation and Mechatronics; Bioengineering; Computer-Aided Engineering and Design; Fluid Mechanics; Heat Transfer, Combustion, and Energy Systems; Manufacturing; Microelectromechanical Systems; Mechanics of Material, and Tribology. The groups in Nuclear and Radiological Engineering are Fission, Fusion, and Medical Physics. The School is the only educational institution to be designated a Mechanical Engineering Heritage Site by the American Society of Mechanical Engineers. The School prepares students for successful careers and lifelong learning by teaching analytical methods, design and data analysis skills, experimental techniques, and the professional and ethical responsibilities of being an engineer. We are the leading producer of master's degrees to women and minorities and among the top producers of bachelor's degrees in mechanical engineering in the country, and we will apply this success towards increasing the number of PhDs received by women and minorities. The School offers programs in mechanical engineering, nuclear and radiological engineering, and health physics. From July 1, 2002 to June 30, 2003, students were awarded more than two million dollars in fellowships for graduate study. The impressive quality of our graduate students is demonstrated by the presence of 114 GT President's Fellows and 113 winners since 1990 of the prestigious National Science Foundation Graduate Research Fellowship.

The graduate program in mechanical engineering is ranked sixth in the nation by U.S. News & World Report and the College of Engineering is ranked fifth. Recent graduates have been hired at universities such as Boston, Cornell, Georgia Tech, Kentucky, Maine, Minnesota, Oklahoma, Penn State, South Carolina, Virginia, and Virginia Tech, and companies such as at General Electric, Lockheed-Martin, Los Alamos National Laboratory, Milliken, Motorola, Raytheon, Sandia, Schlumberger, and Siemens.

School of Physics (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	122	120	107	126	14	22	6.0
Women	16	15	15	18	2	2	6.25
Minorities	9	9	9	11	0	6	6.5

The School of Physics is well positioned to host the proposed IGERT program. GT is nationally recognized for its strength in engineering, and is currently undergoing substantial growth in the physical sciences. There is a planned increase in the School faculty size from 30 to 40 over the next decade; accordingly the School plans to increase the graduate student population from 100 to 150. The level of external funding in the School went up to \$8.1 M from last year's figure of \$6.4 M. The State, with matching funds from various sources, has embarked on an ambitious program to construct new research and teaching facilities at GT, including: the Nanolithography Facility, a \$10M state-of-the-art electron-beam lithography facility due to be installed in early 2004 and the Undergraduate Learning Center, an important addition to the campus where the School plans to conduct recitation sessions for its service-level courses. A particular strength of the School is its interaction with industry. In the recent past, Texas Instruments Hughes Aircraft, Kodak, and the Zygo Corporation have generously contributed funds for the graduate students of the School. The School current enrollment of female graduate students (16%) is higher than the national average (10%). The School has succeeded to raise the percentage of underrepresented ethnic minorities from 6% last year to the 11% mark.

School graduates mentored by the faculty are at several universities including the University of Indiana, Cornell University, University of San Diego, Georgia Tech, University of Tennessee and Emory University. Other Ph.D. graduates have succeeded in the industry, national labs and government agencies such as Newport, Agilent, Los Alamos National Labs, US Army, Air Force, NIA and GTRI. The fact that School of Physics-trained Ph.Ds. are held in high regard is also reflected by the success of graduates obtaining postdoctoral fellowships at several well known institutions including University of Florida, Emory University, Harvard University and Argonne National Labs.

School of Polymer, Textile & Fiber Engineering (2002-2004)

	Applied	Accepted	Enrolled	Current	Withdrawls	PhDs awarded	Time/degree
Applicants	300	51	30	50	15	24	6.0
Women	142	22	12	20	7	5	5.7
Minorities	15	10	2	3	0	0	no degrees

The School of Polymer, Textile & Fiber Engineering (PTFE) was the third engineering school established at GT in 1897. The School currently has 14 faculty members with four new hires in the last year. The School offers courses in polymer science, polymer engineering, textile engineering and color science among others with degrees leading to Bachelor of Polymer and Fiber Engineering, Master of Science in Polymers, Master of Science and Doctor of Philosophy. The School is most interested in attracting and graduating women and minority engineers and scientists. A number of on-campus offices and programs facilitate the recruitment and retention of those students.

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(G) Facilities, Equipment and Other Resources

GT faculty in nonlinear sciences ranked 5th nationally in the most recent U.S. News and World Report nonlinear science standings, and GT commitment to this field is reflected in faculty appointments, centers dedicated to nonlinear science, and infrastructure. Recent faculty appointments include chaired positions in physics (PC) and biomedical engineering (EV), as well as ongoing recruitment efforts for junior/senior appointments in theoretical and experimental nonlinear specialties. Centers dedicated to this field are the School of Math Center for Dynamical Systems & Nonlinear Studies (CDSNS) [43] and the Center for Nonlinear Science (CNS) [34]. CDSNS was founded in 1988 and has been instrumental in developing a strong nonlinear dynamics curriculum. CNS began operation in 2001 and spans nonlinear science efforts by associated faculty across ten science and engineering departments. Over the past three years, the GT seed funding for CNS provided partial support for 3-5 postdoctoral research associates at any given time, a distinguished lecturer series, visitors, workshops, the Nonlinear Science seminars, center administrator, Linux network, and part-time computer/web support.

Beyond these already established nonlinear activities, the GT commitment to this IGERT program consists of IGERT Commons, laboratory space, a visiting faculty office, experimental equipment, and computational facilities. The IGERT Commons is a meeting room that will provide students with computers, white boards and presentation equipment to facilitate discussions and cooperative research efforts. Located in adjoining spaces, the IGERT Commons, the laboratory and visitor office will be central components to the proposed IGERT program.

The IGERT program will require substantial computing resources to implement its objectives. GT's Center for Computational Molecular Science owns a 72-processor IBM SP2, and up to one third of this resource will be available to the IGERT Fellows. Additional infrastructure includes existing computational facilities provided by individual Schools for student use. As a typical example, the Math building houses 40 machines in the undergraduate and graduate computing labs, another 20+ machines in the mobile wireless computing laboratory cart, and a 36-processor (and growing) Beowolf cluster.

The IGERT program will also make use of the CEE Environmental Fluid Mechanics Laboratory, which has approximately 14,000 square feet of floor space and a fully equipped machine shop for both fundamental and applied research. Permanent equipment includes a large constant-head tank, a 14 ft. wide sediment transfer flume, an 80 ft. long tilting flume, several recirculating flumes, a salt-water flume, a density-stratified towing tank, a wave tank, and a wind tunnel. All these experimental techniques are used to study complex flow phenomena encountered in nature and engineering applications. Laboratory measurement techniques include Acoustic Doppler Velocimetry (ADV), Laser Doppler Velocimetry (LDV), Particle Tracking Velocimetry (PTV), Laser Induced Fluorescence (LIF), Schlieren optics, and three-dimensional visualization.