(C) Project Description:

1. List of Participants

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Executive Committee:	
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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

2. 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: – "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 mathematics and physics to engineering to life and atmospheric sciences.
- **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 Atlanta-area historically black colleges and universities (HBCU) to choose 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 either Spelman Women's College or Atlanta Clark University (HBCU institutions), development of a nonlinear science teaching module which is presented 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.

3. Major Research Efforts

Methodology of nonlinear science forms the core of the training proposed under this IGERT program. However, available tools largely fail for systems involving many strongly coupled degrees of freedom. Conceptually new methods applicable to 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 dearth of such methods remains a fundamental barrier for the direct application of nonlinear science to many important outstanding problems.

The IGERT will seek to break this impasse by bringing together teams of IGERT Fellows and faculty with complementary skills; experimental, numerical and theoretical. In what follows, the core faculty listed in sect. (C).1 are indicated by initials, (i.e. [LAB] for L.A. Bunimovich). The GT nonlinear sciences faculty across the campus will take part in Fellow co-advising, as well as other key IGERT activities. Not divisible into neatly disentangled Major Research Efforts, all 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*.

High-dimensional dynamics – observations: In their research, the IGERT faculty explores a broad range of high-dimensional phenomena, on scales ranging from very large to very small. For example:

In medium term climate forecasts, LAS is developing methods which aim 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. Satellite observations are giving us increasingly detailed information about the turbulent dynamics of oceans: EDL, who leads the NSF Long-Term Ecological Research site modelling effort, seeks to uncover mechanisms by which oceanic dynamics affects its biomass by direct Navier-Stokes simulations [3]. PKY carries out some of the nation's most ambitious simulations of turbulent flow using as many as 8 billion grid points to obtain fundamental physical insights about turbulent mixing [4]. CAK seeks to understand the principles underlying the striking patterns in space, time, and organization observed in ecosystems. In the Environmental Fluid Mechanics Laboratory (a proposed training facility for this IGERT) DRW observes flows [5] exhibiting unstable vortices of striking beauty. PJM's simulations of sedimenting suspensions reveal surprisingly rich dynamics. JY's copepods generate characteristic vortex wakes [6]. On still smaller scale, in their development of "opto-microfluidics", MS and RG observe good mixing in optothermally manipulated microdroplets, even though no such mixing is expected [7]. All the way down at atomic scales, ER pursues experimental nanomechanics and nanotribology with Atomic Force Microscopes, and observes counterintuitive nanofluidic behaviors, phenomena with important implications for design of MEMS, "Labs on a Chip" and cell manipulation. [8] At these scales the assumptions underlying continuum fluid dynamics have to be reexamined; the matter is of particular urgency at the cellular level [EV], where enzyme concentration can be as low as 100 enzyme molecules in a cell.

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 research focus of this IGERT: *"How to characterize and control high-dimensional, spatially extended, and very noisy dynamics?"*

High-dimensional dynamics – challenges: Numerical explorations of systems such as hydrodynamics reveal a truly bewildering wealth of solutions. 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 [9]. 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 [10] offers the mathematical implementation of this intuitive picture [PC,LAB]. On the other hand, the MS group possesses a unique skill: by means of their thermally actuated control of thin films [11] pioneered here, 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], and experimental fluid dynamic simulations of such wakes [DRW].

The experience and skills of IGERT's **computational fluid dynamicists** are absolutely essential for any further progress. Pushing the current limits of what is numerically attainable in solving large sets of PDEs, the best we currently can do is write down a set of hydrodynamical PDEs, discretize it on a mesh or a basis function set on the order of 10^4-10^9 components, and follow trajectories in high-dimensional phase spaces. An example of what has been attained so far is the calculation by Kawahara and Kida [12]: 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 $Re = 400$.

Theoretical challenges in analysis and learning to control such systems require understanding 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 Reynolds number regime, 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 physically unrealistic low levels of noise [13].

Stochasticity & nonlinearity: 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 [14] in nonlinear science [KW]. In vitro experiments showed that hair cells exhibit *stochastic resonance*, a counterintuitive nonlinear phenomenon where detection of weak signals is *enhanced* by the presence of external noise.

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]. 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?"*

The challenge of high-dimensional dynamics simply cannot be addressed from the confines of a traditional departmental PhD program. While the IGERT faculty representing such diverse research efforts already offers a vibrant intellectual environment that spans many sciences 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 analysis of turbulent flow [PKY], experimental detection of signal transmission through fluid media [DRW,JY], and information processing of signals acquired 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.

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.

4. Education and Training

In order to address the nonlinear science challenges detailed above, graduate education must transcend traditional departmental boundaries and produce a new breed of scientists of necessary breadth and versatility.

The proposed IGERT training initiative will emphasize the integration of knowledge and foster research independence and self-reliance through a nonlinear science curriculum based on novel lecture-based / project-based courses as well as co-advised independent research. Combined with seminars, internships, workshops and international schools this curriculum will equip IGERT Fellows with the methodology, basic tools and techniques of nonlinear science, as well as an understanding of their applications to specific problems of fundamental and practical significance.

Competitive IGERT Fellowships will be offered to outstanding students pursuing a minor in Nonlinear

Science in conjunction with the PhD degree program in each Fellow's home department. Incoming IGERT Fellows will be introduced to this program with a **Welcoming Workshop/Retreat**, before the start of each Fall semester. Each Fellow will pair up with a nonlinear science advisor, external to her/his home department, who will oversee the Fellow's progress in tandem with a departmental advisor. The IGERT multi-level training sequence, detailed below, is coordinated with the IGERT Fellow's home department core requirements:

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. The same is often true of students from underrepresented groups and small colleges. A new remedial course, to be offered every Fall, will be developed to prepare such students for further courses in Nonlinear Science.

Level 1: Core Techniques of Nonlinear Science
Offered every Spring semester, this lecture-based course will introduce IGERT Fellows to the mathematical and computational techniques of nonlinear science, provide them with basic concepts of nonlinear science (dynamics, stability, bifurcations) and establish a common language bridging the linguistic barriers between disciplines. Numerous elementary examples drawn from physics, biology and engineering will help in developing students' interdisciplinary perspective.

Level 2: Cross-disciplinary Studies of Nonlinear Science
Targeted primarily at the second-year students, this rotating sequence of courses will be based on the research interests of individual faculty and cover applications of the tools and techniques of nonlinear science to problems in physics, chemistry, biology, materials science, and engineering. Examples might include pattern formation, ecological models, or turbulence and mixing. Offered every semester, courses in this advanced sequence can be taken by IGERT Fellows more than once as the topics will change from year to year. The main objectives of this lecture-based course is to demonstrate how the common toolkit of nonlinear science can be used to address different disciplinary problems and to develop initial communication skills necessary for interdisciplinary research. Level 1 and 2 precursor courses [15] are already attracting a wide spectrum of students.

Level 3: Project-based Interdisciplinary Courses
Offered in the Spring semester, this project-based course will stress the development of communication skills. The main objectives will be to provide the second-year students with the collaborative skills and develop the independent learning ability necessary for genuine cross-disciplinary research. The course will be more structured than an independent project would be; with the research focusing on specific projects carried out by small IGERT Fellow teams, supervised by faculty members with complementary expertise and perspectives. The faculty will select the problems and advise the Fellows on the approaches an experienced researcher would employ in similar research settings. A typical project will have a well documented research literature core, leading up to open research questions. Proposed topics include: synchronization in arrays of stochastic elements; pattern formation, selection, and control; mixing and stirring by coherent structures in turbulent flows; and spatiotemporal dynamics of communicating ecological communities.

Level 4: Independent Research
By the third year IGERT Fellows will be expected to have started independent research. This phase of the training program will emphasize the integration of research expertise from several disciplines, for solution of problems lying at their interface. Co-advising, with one advisor from the Fellow's home department and the other selected from the IGERT faculty, will help ensure and nurture the cross-disciplinary focus of each Fellow's research program.

A **Graduate Student Seminar** organized for and by the advanced students will give the IGERT Fellows an opportunity to present their research in a supportive setting, and enhance their communication skills. While the ultimate responsibility for teaching a student the ethical way to conduct research lies with the advisor, this graduate seminar, sometimes run jointly with the parallel IGERT Profession & Ethics seminar, and sometimes advised by the GT Ethics Officer, will also provide a forum for focused discussions on ethics and conflicts of interest in research.

The **IGERT Profession & Ethics Seminar** will offer 3rd year students a semester long course to address such topics as professional advancement, ethics, participation of underrepresented groups, communication skills, conflict resolution, societal priorities, and public policy - all from an interdisciplinary scientific perspective.

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 clearly warrants it, IGERT will sponsor semester-long Fellow internships at international or national nonlinear science sister centers [17], and will in return host interns sent to GT by sister centers.

The courses and projects will envelop IGERT Fellows in an intellectual community that stresses commonalities among disciplines. As the level of courses described above vary from advanced undergraduate to second-year graduate, the sequence will target students both inside and outside of the IGERT program. 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 further key components:

An **Interdisciplinary Nonlinear Science Seminar series** [15], initiated in January 2001, draws a wide attendance across GT and other Atlanta based institutions. IGERT would broaden the scope to engineering and biological applications.

A **visitor program** to promote and maintain national, international, and industrial collaborations, with priority given to visitors whose research demonstrates their potential as external mentors to IGERT fellows.

An annual **Regional Nonlinear Workshop** organized jointly with other Southeastern universities (Duke, U. of Alabama, U. of Florida) will expose students to the cutting-edge research, and give them an opportunity to present their own work.

A **Nonlinear Science School**, a bi-yearly summer school program hosted by the IGERT in conjunction with the CNS and a sister international center, will start with a sequence of tutorial-style lectures, preparing IGERT Fellows as well as students from other participating programs for the research level part of the School.

Our **recruitment and retention** goal 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) help IGERT fellows develop the long-term mentoring network critical to professional success, and (3) teach professional and personal skills that sustain individuals throughout their scientific career.

Our IGERT's **recruitment campaign** will work closely with the ten affiliated graduate programs, especially during their application and admissions cycle. In an effort to attract excellent underrepresented group (URG) candidates, these students will also be eligible for the Goizueta, President's Minority Research, and Patricia Roberts Harris Fellowships. We will advertise our program nationwide, with special efforts to target our top selected 25 feeder institutions and select African-American, American-Indian, Women, Visually-Impaired and Hearing-Impaired Colleges and Universities. Mailings, faculty visits, and faculty contacts will be the primary venues for publicity. All mailings will include a brochure and poster with comprehensive information about our training program.

Once the students are recruited, we will focus on developing a **long-term mentoring network** and a **retention program** that supports their training and professional careers. Persistence and academic success have as much to do with social interactions and social adjustments in the university setting as do variables such as socioeconomic background and academic preparedness. A well-structured mentoring program, with IGERT Assistant Director tracking mentoring and advising relationships, will help URG students avoid isolation by providing them with peers, teachers and role models. To develop a sense of community amongst our students, the educational component of our program emphasizes cooperative projects during courses, group seminars, and workshops.

Our IGERT program will foster and teach professional and personal skills to sustain individuals through-

out their scientific career: leadership, communication, creativity, scholarship, interdisciplinary research, networking, and the ability to work in diverse teams. These skills will be fostered through student organized seminars, workshops, student representation on the IGERT executive committee, cross-disciplinary research, participation in the Profession & Ethics seminar, interaction with seminar speakers, visits with international IGERT faculty, and internship opportunities both domestic and abroad.

5. Management, Assessment, and Institutional Commitment

Management: 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 proposed IGERT, PC will be assisted in the academic program and administrative management functions by the Assistant Director Raenell Soller, an Executive Committee consisting 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 Executive Committee will meet periodically during the academic year, and will administer IGERT fellowships, visitor invitations, international exchanges, diversity-promoting activities, and IGERT budgetary resources in accordance with program goals. The committee will develop and execute a formal mechanism for awarding IGERT fellowships based on the quality and interdisciplinary activity of short proposals that are jointly developed by a student and two or more IGERT faculty.

Performance Assessment: We shall implement a detailed assessment plan aimed at evaluating our progress in promoting interdisciplinary research and education in Nonlinear Science. In preparing our assessment plan we draw upon the experiences of related IGERT, VIGRE and other training grants at GT. The GT Office of Assessment 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 track data on objective measures such as enrollment level in Nonlinear Science courses, time-to-degree for PhD students, research publication activity, recruitment statistics, retention, and participation by underrepresented groups. These findings will be examined by the Executive Committee and presented to the Advisory Board annually. Running assessment data will also be used for mid-course IGERT program improvements in the following areas: **a. Training**. We will track the number and performance of students taking the IGERT interdisciplinary sequence by annual student reviews from the Executive Committee. Student feedback in course evaluations managed by the GT Center for Enhancement of Teaching and Learning will be carefully considered. **b. 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. **c. Diversity**. We will monitor the number of IGERT URG students and compare their academic and research performance with that of other students. In these efforts, we will work with the GT Women in Science and Technology Office, the Office of Minority Education and Development, and the Assistant Dean of Students for Disabilities. **d. The External Advisory Board** (including several PIs of previous IGERTs) will carry out external assessment and provide recommendations for improvements to the program. The Board members will visit GT individually once a year, and collectively for a mid-term program assessment.

Institutional Commitment: GT strongly encourages interdisciplinary activity, with numerous research centers on campus and three currently funded NSF IGERT programs that receive substantial GT assistance. As evidence of this support, GT faculty in nonlinear sciences ranked 5th nationally in the most recent U.S. News and World Report nonlinear science standings. Furthermore, GT commitment to this field is reflected in recent faculty appointments, including 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 Mathematics Center for Dynamical Systems & Nonlinear Studies (CDSNS) [16] and the Center for Nonlinear Science (CNS) [15]. The 2002-2004 seed GT grant to CNS provided partial funding for 3-5 postdoctoral J. Ford Fellows research associates working at CNS at any given time, a distinguished lecturer series, visitors, workshops, the Nonlinear Science seminars, center administrator, and computer/web support. IGERT will build upon this infrastructure already in place, but currently not funded.

GT commitment specific to this IGERT program consists of establishment of IGERT Commons (student meeting/work area), laboratory space, a visiting faculty office, experimental equipment, computational facilities, financial support of the Assistant Director, collaborative recruitment efforts, and curriculum development. The IGERT program will require substantial parallel processor computing resources to implement its objectives, and GT computational centers offers such facilities that are available to all IGERT faculty. The recruitment coordination and curriculum development is already formalized through an agreement between the IGERT Executive Committee and each of the Chairs of the ten participating Schools. In this agreement, each School is committed to (a) providing 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 support their incorporation into the GT curriculum beyond the duration of the IGERT.

6. Other Resources and Connections

As this IGERT is a training program, external resources take two forms; training partners and access to supercomputing. The international aspect of the proposed program is crucial for advancing the 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.

Training. The main **international components** of the proposed IGERT are internships for IGERT fellows abroad, international workshops, and hosting senior visitors and interns from outside the US. The IGERT faculty takes part in many international collaborations, and we have already secured formal IGERT **intern hosting commitments** from a dozen nationally and internationally distinguished scientists who direct our sister international, national or industrial sister institutions. Appended are representative letters from *HRL Laboratories*, Malibu CA, *International Center of Theoretical Physics*, Trieste, Italy (Director is our collaborator K. Sreenivasan), *Spelman College*, and *Oak Ridge National Laboratory*.

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. **Foreign interns hosted** so far have already had significant impact on both research at CNS, and the US students who interacted with the interns. IGERT will provide a framework for enhancing these student exchanges.

We propose that a series of international workshops be initiated and co-organized by the IGERT faculty in tandem with one or more of the 15 sister Nonlinear Centers IGERT faculty collaborates with, located in Argentina, Austria, Chile, Denmark, Germany, Hungary, Israel, Italy, Japan, Mexico, Netherlands and United Kingdom [17]. Specifically, IGERT will initiate the series by hosting a **summer school** in the "Stochastic and high-dimensional nonlinear processes", either in Atlanta or at the Centro Internacional de Ciencias, Cuernavaca, Mexico.

Supercomputing. An Access Grid node links Georgia Tech to over 40 facilities existing worldwide, using Gigabit connections to Internet II and state-of-the-art video conferencing and data streaming technologies. GT is connected to Oak Ridges NSF TeraGrid facility and 22 other Southern universities, currently with 10 teraflops of total computing capability, through the Atlanta GigaPOP or Southern Crossroads (SoX). The Oak Ridge National Laboratory is building a DOE supercomputer to surpass the Earth Simulator in Japan. When completed, GT will have access to the worlds fastest computer. IGERT fellows would also have access to a EU Complexity Network supercomputer situated in Budapest, and similar facilities at sister Max-Planck Institutes in Göttingen and Dresden.

The main external components of the proposed IGERT are (a) internships for IGERT fellows in industry, national labs and abroad, (b) international workshops, (c) hosting senior visitors and interns from outside the US, and (d) access to national supercomputing facilities.

7. Recent Traineeship Experience and Results from Prior NSF Support

Individually, the IGERT faculty already has extensive graduate training records. We highlight here our experiences with several prior or current NSF training grants, and one Danish Natural Sciences Research Council grant as relevant antecedents to the proposed IGERT.

This IGERT proposal integrates the experiences of the Northwestern IGERT (their internship program), the Arizona IGERT (their Biological Physics Teaching Laboratory) and the Cornell IGERT, all three very successful programs. Only Cornell IGERT is currently funded.

P. Cvitanović has considerable experience in running cross-disciplinary programs of the proposed scope. He co-founded and directed (1993-1998) the *Center for Chaos and Turbulence Studies* [18] at the Niels Bohr Institute, Copenhagen, a cross-disciplinary effort which has evolved to be one of Europe's leading centers for nonlinear science, with approximately 80 faculty, post-docs, graduate students, and long term visitors, and 5 workshops/conferences in any given year. The synergy of this "Copenhagen School" continues to this day through the `ChaosBook.org` collaboration, a hyperlinked web-based course [10] which the proposed IGERT would develop further as an outreach effort. In the period 1997-2000, prior to moving to GT, PC was instrumental in assembling the cross-disciplinary team that led to the award (with PC as the original PI) of the **IGERT #9987577**: *Complex Systems in Science and Engineering program* (Northwestern 2001-2005) [19]. Ably led by H. Riecke, experiences of the Northwestern IGERT were invaluable in formulation of this proposal.

L.A. Bunimovich was co-PI and the Director of **GIG #9632032**: *Southeast Applied Analysis Center* (GT 1996-2002). Several outreach activities of this proposal, such as offering lecturers in mathematics, natural sciences and engineering to regional URG institutions, build upon the initiatives pioneered by and contacts established by SAAC [20], in particular the *SAAC ambassadors*, who delivered lectures on various forefront topics of modern mathematics in regional universities and colleges.

It is worth following professional trajectories of former SAAC and CNS research associates. SAAC's B. Guenin is the recipient of the 2000 MPS Tucker Prize, the 2003 MPS/AMS Fulkerson Prize and the 2004 SIAM Outstanding Paper Prize. SAAC's R. Latala was invited speaker at the 2002 Internat. Congress of Mathematicians. All four former CNS J. Ford fellows have moved to permanent academic positions at research universities.

IGERT faculty D.R. Webster (fluid dynamicist) and J. Yen (ocean biologist) have valuable experience from being on the team of the **IGERT #0114400**: *Signals in the Sea* (GT 2001-2006) whose focus is biology, marine ecology, and environmental engineering. The key skill acquired was the success in designing interdisciplinary courses tuned to needs of students from varied disciplines, most of whom do not have all the prerequisites needed. Another success of the *Signals in the Sea* IGERT that we build upon is their innovative Ethics Seminar.

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. Following this model, our IGERT will be administered by a full time Academic Professional, critical to mounting a rigorous effort at recruitment and retention.

(D) References Cited

[1] "Physics in a new era: an overview," *National Research Council report* (National Academy Press, Washington, D.C., 2001); www.nap.edu/books/0309073421/html/.

[2] Interview with GT President Clough, *Technique* (March 22, 2002); www.cns.gatech.edu/CNS/Clough.html.

[3] E. Di Lorenzo, A.J. Miller, D.J. Neilson, B.D. Cornuelle, and J.R. Moisan, "Modeling observed California Current mesoscale eddies and the ecosystem response," *Internat. J. of Remote Sensing* **25** 1307 (2004).

[4] P.K. Yeung, D.A. Donzis and K.R. Sreenivasan, "Turbulence and scalar transport in numerical simulations at 2048^3 resolution," *Bull. Am. Phys. Soc.* **49**, 22 (2004).

[5] D.R. Webster, A. Brathwaite, and J. Yen, "A Novel Laboratory Apparatus for Simulating Isotropic Oceanic Turbulence at Low Reynolds Number," *Limnology and Oceanography: Methods* **2**, 1-12 (2004).

[6] J. Yen, "Life in transition: balancing inertial and viscous forces by planktonic copepods," *Biol. Bull.* **198**, 213 (2000).

[7] R.O. Grigoriev and M.F. Schatz, "Optically controlled mixing in microdroplets," in *Proc. 42nd AIAA Aerospace Sciences Meeting* 2004.

[8] E. Riedo, E. Gnecco, R. Bennewitz, E. Meyer and H. Brune, "Interaction Potential and Attempt Frequency Governing Sliding Friction," *Phys. Rev. Lett.* **91**, 084502, (2003). (Highlighted by Virtual Journal of Nanoscale Science & Technology, 2003)

[9] Y. Lan and P. Cvitanović, "Variational method for finding periodic orbits in a general flow," *Phys. Rev.* **E 69**, 016217 (2004).

[10] P. Cvitanović *et al.*, *Chaos: Classical and Quantum;* advanced graduate web course, ChaosBook.org.

[11] D. Semwogerere and M.F. Schatz, "Secondary instabilities of hexagonal patterns in a Bénard-Marangoni convection experiment," *Phys. Rev. Lett.* **93**, 124502 (2004).

[12] G. Kawahara and S. Kida, "Periodic motion embedded in plane Couette turbulence: regeneration cycle and burst," *J. Fluid Mech.* **449**, 291 (2001).

[13] R.O. Grigoriev and A. Handel, "Spectral Theory for the Failure of Linear Control in a Nonlinear Stochastic System," *Phys. Rev.* **E 66**, 065301R (2002).

[14] K. Wiesenfeld and F. Moss, "Stochastic resonance and the benefits of noise: from ice ages to crayfish and SQUIDs," *Nature* **373**, 33 (1995).

[15] Center for Nonlinear Science, www.cns.gatech.edu; see "Courses", "Seminars", "Research" links.

[16] Center for Dynamical Systems & Nonlinear Studies, www.math.gatech.edu/cdsns.

[17] www.cns.gatech.edu/centers/sorelle.html and sisters.html.

[18] Center for Chaos And Turbulence Studies, www.nbi.dk/CATS.

[19] Northwestern U. Dynamics of Complex Systems in Science and Engineering, www.complex-systems.northwestern.edu.

[20] The Southeast Applied Analysis Center, www.math.gatech.edu/saac.