(C) Project Description:

a. List of Participants

[1] [2]

Director:

Predrag Cvitanović, Glen Robinson Chair, Professor, School of Physics (COS)

Executive Committee:

Leonid A. Bunimovich, Regents' Professor, School of Mathematics (COS)

Kurt Wiesenfeld, Professor, School of Physics (COS)

Jeannette Yen, Deputy Dir. for COS, Professor, School of Biology (COS)

P.K. Yeung, Associate Professor, Deputy Dir. for COE, School of Aerospace Engineering (COE)

Faculty:

[1]NSF requires: **(1-page limit)**: Include departmental and institutional affiliation of all faculty members and other senior level personnel expected to have an important role in the project.

[2]NSF requires: List of Participants. List each senior investigator (faculty level or equivalent), by full name, and his or her institutional and departmental affiliation. Enter in "Add/Modify Non CO-PI Senior Personnel" FastLane form.

Y.H. Chen, Associate Professor, School of Mechanical Engineering (COE)

E. DiLorenzo, Associate Professor, School of Earth and Atmospheric Sciences(COS)

R.F. Fox, Regents' Professor, Chair of School of Physics (COS)

G. Goldsztein, Assistant Professor, School of Mathematics (COS)

R. Grigoriev, Assistant Professor, School of Physics (COS)

E.M. Harrell, Professor, School of Mathematics(COS)

R. Hernandez, Co-director CCMST, Associate Professor, School of Chemistry (COS)

C.A. Klausmeier, Assistant Professor, School of Biology (COS)

K.E. Kurtis, Assistant Professor, School of Environmental and Civil Engineering (COE)

P.J. Mucha, Assistant Professor, School of Mathematics (COS)

G.P. Neitzel, Professor, School of Mechanical Engineering (COE)

E. Riedo, Assistant Professor, School of Physics (COS)

M.F. Schatz, Associate Professor, School of Physics (COS)

L.A. Smith, Reader in Statistics, London School of Economics

M. Srinavasarao, Associate Professor, School of Polymer, Textile and Fiber Engineering (COE)

L. Ting, Assistant Professor, Georgia Tech/Emory Biomedical Engineering Department(COE)

T. Uzer, Professor, Physics (COS)

E. Voit, Georgia Research Alliance Eminent Scholar in Systems Biology, Professor, Georgia Tech/Emory Biomedical Engineering Department(COE)

D. Webster, Associate Professor, School of Civil & Environmental Engineering

M. Yoda, Associate Professor, School of Mechanical Engineering(COE)

H.M. Zhou, Assistant Professor, School of Mathematics (COS)

The key to the school and departmental abbreviations used throughout the proposal:

GT	Georgia Institute of Technology
COS	College of Sciences

COE	College of Engineering
AE	School of Aerospace Engineering
Bio	School of Biology
BME	Georgia Tech/Emory Biomedical Engineering Department
Chem	School of Chemistry and Biochemistry
CE	School of Civil & Environmental Engineering
EAS	School of Earth and Atmospheric Sciences
Math	School of Mathematics
ME	School of Mechanical Engineering
Phys	School of Physics
PTFE	School of Polymer, Textile and Fiber Engineering
CCMST	Center for Computational Molecular Science & Technology
CDSNS	Center for Dynamical Systems & Nonlinear Studies

b. Vision, Goals and Thematic Basis

[3] [4] Nonlinear science impacts a broad spectrum of disciplines: for example, the Topical Group on Statistical and Nonlinear Physics and the Activity Group on Dynamical Systems are today among the most active within APS and SIAM, respectively. However, today nonlinear science also faces very hard challenges. In a 2001 report "Physics in a New Era: an Overview" [1] the National Research Council has identified six "grand challenges". Three of the six – "understanding complex systems", "applying physics to biology", and "creating new materials" – demand conceptually new methods for dealing with systems with many degrees of freedom in strongly stochastic environments. These are problems with no clear boundaries between physics, mathematics, engineering and life sciences.

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 in the tools and methods of nonlinear science that bridges departmental boundaries, 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. GaTech has an exceptionally strong community of experts in high-dimensional dynamics: fluid mechanics, pattern formation and control, 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 in many fields, from math and physics to engineering.
- **Training in cross-cutting methodologies**, stimulating cross-disciplinary research and communi-

[3] NSF requires: Limit the narrative to a combined **total length of 7 pages**, inclusive of list of participants (1 page), tables, figures, or other graphical data. Describe the vision, goals, and anticipated impact of the proposed IGERT project. Describe the thematic basis and unifying aspects of the interdisciplinary research and educational activities to be offered. Include a discussion of what is currently missing from graduate education and training or what could be done more effectively, and how the proposed project will address these issues. Summarize the value-added aspects of the proposed project, and be specific about what is new and innovative. (Limit: 1 page)

[4] **file** vision.tex - Apr 28 2004

cation skills through a balanced core curriculum that includes both lecture-based and project-based courses. A key innovation is an early research experience, invovling small teams investigating topics 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 student-run seminars, regional workshops, and a visitor program. Global perspective will be enhanced through internships and summer schools with sister institutions abroad.

- **Outreach**: GaTech has a notable record in minority recruitment and retention [2]; the IGERT program will encourage undergraduates from historically black Atlanta-area colleges (Clark-Atlanta, Morris-Brown, Morehouse and Spelman) to chose a career in science or engineering, by involving them in IGERT summer research projects. Educational outreach will be also served by the development of a web-based advanced nonlinear science course.

- **Strategic impact**: GaTech is the premier science and technology institution in the Southeast, with strong state and industrial support. Already possessing a leading program in nonlinear science, GaTech teams up faculty in cross-disciplinary facilities and is moving aggressively into several allied areas, establishing new centers in nonlinear science, bioinformatics, biomedical engineering, and large scale computing.

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 more narrow graduate degree programs. ⇓PRELIMINAR

RY

c. Major Research Efforts

[5] [6] 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).a are indicated by initials, (i.e. [LAB] for L.A. Bunimovich). The GaTech 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. PKY carries out some of nation's largest supercomputer numerical simulations of the exact Navier-Stokes equations, employing more than 10^9 grid points, in order to elucidate turbulent

[5] NSF requires: Describe the major research efforts that are intended to serve as the foundation of the IGERT project. Emphasize their cutting-edge aspects and how they are interwoven and integrated to form the thematic basis for the interdisciplinary project. They should be described in sufficient detail for reviewers to assess their scientific merit and relevance to the project theme. If an international component is included, describe how it is to be grounded in the core research, education, and training activities of the IGERT project.

[6] **file** research.tex - Apr 28 2004

diffusion and mixing in the atmosphere [3]. CAK seeks to understand the principles underlying the striking patterns in space, time, and organization observed in ecosystems. PJM's simulations of sedimenting suspensions reveal surprisingly rich dynamics. DRW's Navier-Stokes simulations of a hydro-mechanical "??" reveal beautiful unstable vortices [**?**]. JY's copepods generate characteristic vortex wakes [4], see fig. 2. 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 [5]. At atomic scales ER observes counterintuitive nanofluidic behaviors with implications for design of MEMS, "labs on chip" and cell manipulation. 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?"*

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 [6]. 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 [7] 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 [8] pioneered here [MS] they are able to *design* spatio-temporal patterns, and thus create and test ex-

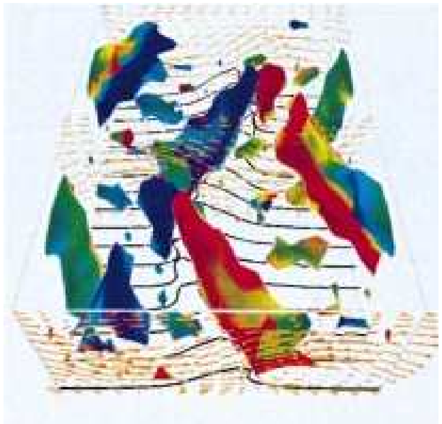

Figure 1: *A 3-d instantaneous snapshot of an unstable periodic solution embedded in Couette turbulence [9]. Vectors and color code velocities and vorticities.*

perimentally 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 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 [9]: 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 $Re = 400$, see fig. 1.

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 [20].

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 [10] in nonlinear science [KW]. In vitro experiments [11] showed that hair cells exhibit *stochastic resonance*, a

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

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?"* [7]

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. 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,DRW], experimental detection of signal transmission through fluid media [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.

[7] PC: rephrase

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

[8] [9] [10] [11]

Georgia Tech's IGERT Program in Nonlinear Science will be broadly interdisciplinary, bringing together faculty from ten departments, as well as several scholars at other institutions. We will develop a curriculum centered on a new set of 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 tools and techniques of nonlinear science, as well as an understanding of their applications to fundamental and practical problems.

Students will be recruited with competitive IGERT Fellowships to study in any of the participating departments. [12] Each Fellow will pursue one of the usual PhD degree programs in a home unit, and at the same time will pursue a structured minor in Nonlinear Science. Georgia Tech has long had a large number of interdisciplinary research collaborations and degree programs. On occasion this has included doctoral students with co-advisors from different departments. The IGERT program will build on this experience. After the **Welcoming Workshop/Retreat**, described more fully below, incoming Fellows will be paired up

[8] **file** education.tex Oct 9 2004

[9] NSF requires: The IGERT program has been developed to meet the challenges of educating U.S. PhD scientists, engineers, and educators with the interdisciplinary backgrounds, deep knowledge in chosen disciplines, and technical, professional, and personal skills to become in their own careers the leaders and creative agents for change. The program is intended to catalyze a cultural change in graduate education, for students, faculty, and institutions, by establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries. It is also intended to facilitate greater diversity in student participation and preparation, and to contribute to the development of a diverse, globally-engaged science and engineering workforce.

[10] NSF requires: Describe the graduate education and training mechanisms that are central to the IGERT project, the logic and evidence to support them, and how they are to be integrated with the research and across the disciplines. Novel aspects should be emphasized to enable assessment of the innovation and potential impact. Specify faculty members and other participants with primary responsibility for these integrative efforts. Describe strategies for developing a community of students. Discuss plans for providing career development opportunities, developing professional and personal skills, fostering an international perspective and ability to work in diverse teams, and integrating instruction in ethics and the responsible conduct of research. If planned student training includes internships, fieldwork, or other opportunities, domestic and foreign, identify the potential mentors and discuss how the opportunity is intended to strengthen both a student's graduate experience and the IGERT project. If proposed, discuss the benefits of international research experiences (e.g. quality of research partners, development of long-term international research partnerships, etc.). Supporting letters from host organizations should document willingness to receive students and the expected role of individual mentors. Show typical student pathways through the program and the effect on expected time to degree and career progression. The role of undergraduate, masters, and postdoctoral components, if proposed, must also be described with sufficient detail to clarify the benefit to the doctoral program and to justify support through this type of award.

[11] EMH: OLD STUFF ELIMINATED BECAUSE TRANSCENDENCE SCARES ME: 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, etc. etc.

[12] EMH: Is there a specific list of core departments?

with a nonlinear science advisor, outside the Fellow's home department. The nonlinear science advisor will work together with an academic advisor in the home department, to make sure that the Fellow is adequately prepared for the program, particularly the parts outside the Fellow's major.

Georgia Tech already has in place a well-developed curriculum in nonlinear science in several departments (see below). Many courses in the catalogue are cross-listed so that they can be taught in more than one department. The departments participating in IGERT will fine-tune the course descriptions for the courses in nonlinear dynamics, and will create new cross-listed courses, in response to IGERT's needs. The Graduate Coordinator in the major department will work with the Fellow to coordinate department core requirements with the following four-level training sequence.

Level 0: Introduction to Nonlinear Science

Georgia Tech already has special courses, which have been designed to help graduate students in interdisciplinary programs fill out weaknesses in their preparation outside their major. In particular, biology students traditionally lack the mathematical background required by most nonlinear science courses. Students lacking the necessary prerequisites will take in the Fall semester of their first year an introductory course Modeling and Dynamics (Math 6705). Originally designed for Georgia Tech's bioinformatics MS/PhD program, the course typically attracts about 25 graduate students, including those from biomedical engineering, biochemistry, and other areas of biological sciences.

The course only assumes the knowledge of single variable calculus and basic linear algebra. Using case studies in population dynamics (both discrete and continous), kinetic equations, pharmacokinetic models, biophysical models of neurons, gene networks, and disease dynamics the course introduces the basics of matrix theory, ordinary differential equations, deterministic dynamics, Markov processes, statistics, and numerical methods. The course also includes a final project in which students reproduce calculations from an instructor-approved research paper in a topic of their choice, try to extend them, and present the compilation of the old and new results as well as relevant background material in the form of a term paper.

Level 1: Foundations 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 excellent 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, Machanical and Aerospace Engineering.

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

Level 2: Applications of Nonlinear Science.

Primarily for second-year students, this rotating sequence of lecture-based courses will be based on the research interests of faculty and cover applications of nonlinear science to problems in physics, chemistry, biology, materials science, and engineering. Offered every Fall semester, this advanced course can be taken by IGERT Fellows more than once, as the topics will change from year to year.

Another objective of this lecture-based course is to develop Fellows' communication skills necessary for interdisciplinary research. Examples of Level 1 and 2 precursor courses [12], which are already attracting a wide spectrum of students at Georgia Tech, include:

- 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, contractions 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 and conducting their analysis using a general framework based on the symmetry based classification of solutions to common partial differential equations, the analysis of their linear stability and bifurcations. The course also covers advanced aspects of pattern formation such as nonlinear saturation and pattern selection, and the dynamics of weakly disordered patterns. Together with the Statistical Mechanics course described below this course provides students with the basic mathematical tools for studying the dynamics of high-dimensional noisy systems. The prerequisites for this course include the basic knowledge of linear algebra, partial differential equations, and bifurcation theory.

- Statistical Mechanics II (PHYS 7123)

  The course describes the principles of nonequilibrium statistical mechanics, both classical and quantum. Emphasis is on the dynamics of fluctuations, their measurement, and their relationship to transport properties. Covered topics include Stochastic Processes (Random Walks and Flights, Langevin Equations, Fokker-Planck Equations) and their applications and Critical Phenomena (Scaling, Universality, Landau Theory, Renormalization Group).

  $\rightarrow$ Need to provide a better description $\leftarrow$.

- Fluid Mechanics of Organisms (CEE 6263)

  The objective is to apply principles of fluid mechanics to the context of biological organisms. Flows inside and around organisms are analyzed, and the effect of fluid mechanics on behavior and evolutionary trends are discussed. Lecture topics 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 J. Exp. Biology, Nature, Science, Limnology and Oceanography, and other journals. The course is taught at the graduate level, challenging engineering and physics students, with limited biology background, and biology and chemistry students, with limited fluid mechanics background.

- 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. The transition between modules highlights the increasing complexity of the following section. 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.

- Mathematical Biology () Klausmeier

- Biochemical Systems Analysis () Voit

Other courses 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), Group Theory (PHYS 7143), and Renormalization Group Theory (PHYS 8803).

Level 3: Advanced Topics in Nonlinear Science. Offered in the Spring semester, this project-based course will stress communication skills. Other objectives will be to develop collaborative skills and to foster genuine cross-disciplinary research. The course will be more structured than an independent project would be, with specific research projects carried out by small teams of Fellows under faculty supervision. The faculty will be selected for diversity of expertise and perspective, and will advise the Fellows how an experienced researcher would approach the research. The core of a typical project will be a well-documented literature search and the identification of open research questions. Below we outline several possible topics.

- Multi-scale Physical-Biological Interactions in Oceans: The response of aquatic organisms to large to small-scale fluid physical dynamics in the oceans will be described, modeled, and experimentally demonstrated, thus combining biological and physical oceanography, fluid mechanics, and numerical simulation. For independent projects, students will form groups of 3 (biologist, engineer, mathematician) to work together to perform sensitivity analyses, theoretical considerations and experimental tests. Examples include: a) The Gulf Stream guides eels to their nesting site, b) Thin Layers attract planktonic aggregations, c) Turbulent Eddies orient individual plankters, d) Aquatic Food Web dynamics in response to mixing. Professors: J. Yen (Biology), P.K. Yeung (Aerospace Engineering), E. Di Lorenzo (Earth and Atmospheric Sciences), D. Webster (Civil and Environmental Engineering), C. Klausmeier (Biology).

- 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. An experimentalist might use the results to study how diffusion affects the accuracy of micro- and nanoscale particle image velocimetry or molecular tagging velocimetry – both diagnostic techniques of interest in micro- and nanoscale fluidics. Professors M. Yoda (Mechanical Engineering) and P. Mucha (Mathematics).

- Understanding Turbulence Using Direct Numerical Simulations: Students will adopt a post-processing code to extract detailed physical information from an extensive database of DNS data archived from previous work by PKY's research group. Students are encouraged to formulate their own research questions to be answered by the data analysis. Professors P.K. Yeung (Aerospace Engineering) and D. Webster (CEE).

- Effects of Microstructure in Macroscopic Properties of Materials: Students will learn and use both computational and analytical methods to explore the dependence of material properties on the material microstucture. Possible materials to be studied are: composites, polycrystals and porous media. Professors G. Goldzstein (Mathematics) and K. Kurtis (CEE).

- Pattern Formation, Selection, and Control: students will study experimentally pattern formation in several canonical fluid systems (Rayleigh-Benard and Marangoni convection, contact line instability in spreading films) in the lab of Professor M. Schatz. They will also learn to control the patterns using passive and active feedback control techniques. The student will also learn theoretical foundations of control using a range of models, from very simple to quite realistic. These studies will guide their experimental work. Professors R. Grigoriev, M. Schatz (Physics) and Y.H. Chen (Mechanical Engineering).

Level 4: Independent Research

By the third year IGERT Fellows are expected to have begun independent research. In this phase of the training program Fellows will integrate expertise from several disciplines to solve problems at their interface. All IGERT Fellows will be co-advised, with one advisor from the Fellow's home department and the other one external.

A **Welcome Retreat** blah blah blah

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 GaTech IGERT ethics seminar, and sometimes advised by the GaTech Ethics Officer, [13] will also provide a forum for directed discussions on ethics and conflicts of interest in research.

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 3-6 month Fellow internships at international or national nonlinear science sister centers [14, 15], and will in return host interns sent to GaTech 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, thus enhancing the quality of the IGERT Fellows' research environment.

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 GaTech. Much of the cross-disciplinary GaTech research already has a significant international component, and an intern might be hosted by Bayreuth University, the Niels Bohr Institute (Copenhagen), the Max-Planck-Institute for Complex Systems (Dresden), or another sister center, in order to receive additional training in experimental or theoretical pattern formation, and complex fluids programs.

The courses and projects will envelop IGERT Fellows in an intellectual community that stresses commonalities among disciplines. As the level of courses described above will vary from advanced undergraduate to second-year graduate, the sequence will target the range of students, both inside and outside of the IGERT program. The recruiting efforts will also benefit from another IGERT initiative, a web-based year-long

[13] PC: cross-check

advanced graduate nonlinear course [7], reaching students well beyond GaTech. The IGERT competitive Fellowship will assist in recruitment of the very best students, making careers in science/engineering more attractive to a wider range of students. IGERT Fellowships will be used exclusively to support co-advised Fellows, enabling them to concentrate on study and research during the first two years of their PhD programs. [14] 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** [13], initiated in January 2001, draws a wide attendance across GaTech 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 demonstrate potential as external mentors to IGERT fellows.

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 professional activities. For these purposes, the main body of the organizing committee will be consisted by senior graduate students and junior faculty members with students playing the leading roles and faculties providing consultations. The workshop will have a broad scope, covering different branches of the nonlinear science in different disciplines. This broad scope will give the students the 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. About six speakers, majority are graduate students and junior faculties from regional universities, will showcase their recent interesting research results. Two world leading external researchers will be invited

[14] PC: recheck new IGERT rules

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. In additional, 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. [15]

Nonlinear Science 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 a condensed learning opportunity to prepare IGERT fellows and students from other participating institutes 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 host a summer school in the "Stochastic and high-dimensional nonlinear processes", either in Atlanta or at the Centro International de Ciencias, Cuernavaca, Mexico [14]. In addition, about six national and international researchers will be invited to give colloquium-style presentations on the most recent provoking forefronts in nonlinear science.

[15] PC: be specific

e. Management, Assessment, and Institutional Commitment

[16] ⇓PRELIMINAR

[16] NSF requires: Describe the strategies for management of the IGERT project, for formative and summative assessment of the projects effectiveness in its impact on students and faculty, and the commitment that the institution will make to furthering project plans and goals and to creating a supportive environment for interdisciplinary research and education. Indicate how diversity will be promoted as an integral part of the project.

RY

[17] 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 GaTech Center for Nonlinear Science. In the period 1993-1998 Cvitanović founded and directed *Center for Chaos and Turbulence Studies* at the Niels Bohr Institute, Copenhagen, a cross-disciplinary effort which became one of Europe's leading centers for nonlinear science involving approximately 15 faculty, 8 post-docs, 45 graduate students, 50 long- and short-term visitors and about 5 workshops/conferences in any given year. Prior to moving to GaTech PC led the initiative to create a complex systems program at Northwestern University, and served as original PI on a successful IGERT proposal (Grant PGE-9987577, see Sec. C.g). In the new IGERT PC will be assisted in various management functions by a part-time Administrator (RS) and an *Executive Committee* which includes four other faculty members with expertise stretching across traditional disciplinary boundaries. (Initially they will be LAB, KW, PKY and JY, who are all listed as project co-PIs; JY and PKY will also serve as project deputy-directors and as main liasions with Colleges of Sciences and Engineering respectively.)

The *Executive Committee* will meet at least once monthly and be responsible for administering the award of IGERT fellowships, visitor invitations, international exchanges, and managing IGERT budgetary resources in accordance with the goals of our program. In particular the EC 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 more IGERT faculty preferrably in different academic units, without regard for faculty status (e.g being PI or co-PI, nor academic rank). The actions of this Committee will be responsive to input from other IGERT faculty, and from an *External Advisory Board* [EAB, see Sec C.f below]. The latter shall consist of at least three invited experts in nonlinear science, each of whom shall visit about once a year, and togethe for the EAB mid-term visit (year 3).

The institutional environment at GaTech encourages interdisciplinary activity. Among the numerous Research Centers on campus are two currently IGERT projects which have received substantial commit-

[17]**file** organization.tex - Oct 7 2004

ments of cost-sharing and other administrative assistance from the Vice-Provost of Research and Graduate Studies. We have received commitments of institutional support including cost-sharing at three different administrative levels. In particular:

- All School Chairs involved have indicated that they are strongly supportive of this proposal and their participating faculty. The individual School's formal commitments shall include, at least: (a) supporting students on regular assistantships in the first year on State funds before their two-year tenure as IGERT fellows, and afterwards if funds from the faculty advisors' individual research grants are not sufficient; (b) asking associate chairs and graduate program coordinators to work with us in recruitment of strong graduate school applicants; (c) designating a portion of faculty teaching load to courses related to this IGERT; and (d) supporting faculty initiatives in developing new courses and steering these courses through the official approvals process involving campus curriculum committees. A sample letter of support from the Chairs of (SUGGESTED) Physics (HOME OF PI) and Mechanical Engineering (HAVING MOST FACULTY ON THE LIST FROM COE) are attached.

- The Colleges of Science (COS) and of Engineering (COS) have both committed to.......... Supporting letters from both Deans' offices are attached.

- The Vice-Provost for Research and Graduate studies (C. Liotta) has committed to.................... A supporting level from the Vice-Provost is attached.

The faculty involved in this project 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.

.... Discuss plans for sustaining key features of the project after NSF funding ends...........

[18]

We shall implement a detailed assessment plan which is aimed at evaluating our progress in promoting interdisciplinary research and education in Nonlinear Science, including considerations for human resource development. The Office of Assessment at GaTech has committed to assist us in soliciting (anonymously if appropriate) feedback from students, faculty, internship hosts and visitors involved in our program. Our Administator and Assistant Director will collect annually data on objective measures such as enrolment level in Nonlinear Science courses, time-to-degree for PhD theses, research publication activity; and in addition will compile statistics on recruitment, retention, and under-represented group participation. These findings will be examined by the *Ex-Co* and presented to our *EAB* regularly and during their on-campus visits. Several examples of how assessment results will be used to make improvements are the following:

1. We will track the number and performance of students taking interdisciplinary courses or courses offered by a cross-displinary major . If enrolment levels are low we may try to improve advertising and modify course contents to match more closely with student and program needs. If insufficient interdiscplinary background is a concern in limiting student achievement the instructors will provide expanded coverage of basic prerequisites both in class and through extra tutorial sessions. Student feedback in course evaluations managed by the Center for Enhancement of Teaching and Learning on campus will similarly be given careful consideration.

2. We will look for evidence of interdisciplinary thinking and research contributions, including publications by faculty and students in inter- or cross-disciplinary journals and presentations at professional conferences of a similar nature. We will use the assessment data to identify areas where interdisciplinary collaborations are more difficult and direct our resources to meet specific needs, e.g. by seminars and workshops aimed at promoting cross-talk between different research communities.

3. For diversity issues we will monitor the number of IGERT students belonging to underrrepresented

[18] **file** assessment.tex - Oct 7 2004

groups and compare their academic and research performance with that of other students. We will also work with other campus offices (e.g. Women in Science and Technlogy, Office of Minority Education and Development, Office of Assistant Dean of Students for Disabilities) devoted to students in these categories. We will also monitor the size of the recruitment pool which is likely to be small compared to the general student population. .... What can we do based on the data ? ....

4. The *External Advisory Board* will carry out functions of external assessment and provide recommendations for continual improvements of our program. We shall ensure that at least one board member has deep experience in science management (or be a previous IGERT grantee or NSF program official) so that he/she would have a broad perspective in comparing our program with others objectively. We view as crucial comments and recommendations from the *EAB* and from our international partners about the students that they host.

⇓PRELIMINAR

RY

f. Other Resources and Connections

[19] [20] [21]

GaTech faculty in nonlinear sciences was ranked 5th nationally in the 1999 U.S. News and World Report survey. GaTech's commitment to this field is reflected in the chaired faculty appointment in physics (PC), and continued recruiting efforts in mathematics and physics (junior and/or senior experimental nonlinear physics searches in 2001-05), and the expansion in biosciences, including a biophysics chair search. coupled to the planned expansion of both Schools. As a seed contribution, GaTech committed $147K/year for the fiscal years 2002-2004, providing partial funding for 3-5 postdoctoral research associates working at CNS at any given time, a distinguished lecturer series, visitors, workshops, the Nonlinear Science seminars, center administrator, part-time computer/web support. Also ca. $80K is endowed annually for a Nonlinear Sciences Chair, and $30K was provided to cover the equipping of research associates' offices, research infrastructure (such as a Linux network which is a platform for intensive computation) and office equipment.

GaTech has a long-standing record of encouraging cross-departmental and cross-disciplinary research training. The School of Math CDSNS [35], founded in 1988, has been instrumental in developing a strong nonlinear dynamics curriculum. The *GaTech Center for Nonlinear Science* (CNS) which began operation in 2001, already spans nonlinear science efforts across eight science and engineering departments [17]. [22] The IGERT office and the common meeting room will be housed in CNS, Howey Physics building. Shared office space and computer facilities will be provided to the IGERT Fellows, with the IGERT experimental training laboratories housed in proximity to the participating faculty laboratories. An experimental computation laboratory is operational in the Math building. The IGERT program will require substantial parallel

[19] NSF requires: Describe anticipated resource commitments to the IGERT project by other organizations expected to participate, such as industry, government, non-U.S. institutions, and private foundations. Applicants proposing international activities may wish to consult the INT member of the IGERT Coordinating Committee, listed in Section VIII, Contacts.
[20] **file** resources.tex - Oct 6 2004
[21] PC: throughout: always stress things that would not happen without IGERT
[22] PC: recount the no. departments

processor computing resources to implement its objectives. GaTech's Center for Computational Molecular Science and Technology, already provides a 72-processor IBM SP2. Up to one third of this resource will be available to the IGERT Fellows.

[23]

g. Recent Traineeship Experience and Results from Prior NSF Support

[24] [25]

Two prior NSF grants form the basis for this IGERT preproposal: P. Cvitanović, PI (until moving to GaTech) - **IGERT #9987577**: Northwestern University *Dynamics of Complex Systems in Science and Engineering* (2000-2004), and L.A. Bunimovich, CoPI and Director - **GIG #9632032**: *Southeast Applied Analysis Center* (1996-2001).

Our faculty follows closely activities of the Northwestern, Arizona, Cornell and GaTech IGERT programs; significant aspects of this proposal incorporate our colleagues' IGERT experiences. The student satisfaction with the programs is high, and they are an invaluable resource in breaking down departmental walls.

European PhD programs typically require that their students spend 3-12 months abroad, with support from their home institutions. As the former Secretary of European Dynamics Days Advisory Committee, 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.

[26]

[23] PC: ASK Schuster: In addition, if this proposal is funded, GaTech will support additional graduate students in the IGERT program (the precise number to be negotiated), cover the differential tuition for out-of-state graduate students, and match the capital equipment expenditure of the IGERT experimental and computational training program.

[24] NSF requires: Describe your experience with and outcomes of any related graduate traineeship project during the past five years. In this description, address not only the outcomes of the prior project, but also, in a comparative manner, describe the value-added aspects of the proposed IGERT project.

[25] **file** prior.tex - Apr 27 2004

[26] PC: add Mogul collaboration in Predrag's CV

27 28

(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] B.L. Sawford, P.K. Yeung, M.S. Borgas, P. Vedula, A. LaPorta, A.M. Crawford, and E. Bodenschatz, "Conditional and unconditional acceleration statistics in turbulence," *Phys. Fluids* **15**, 3478 (2003).

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

[5] N. Garnier, R.O. Grigoriev and M.F. Schatz, "Optical manipulation of microscale fluid flow," *Phys. Rev. Lett.* **91**, 054501 (2003).

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

[7] P. Cvitanović *et al.*, *Chaos: Classical and Quantum*, advanced graduate course, available electronically at `ChaosBook.org`.

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

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

[27] NSF requires: 1 page limit, separate from the project

[28] **file** refs.tex - Sep 21 2004

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

[11] F. Jaramillo and K. Wiesenfeld, “Mechanoelectrical transduction assisted by Brownian motion: a role for noise in the auditory system,” *Nature Neuroscience* **1**, 384 (1998).

[12] `www.cns.gatech.edu/courses`

[13] `www.cns.gatech.edu/research`.

[14] `www.cns.gatech.edu/centers/sorelle.html`.

[15] `www.cns.gatech.edu/centers/sisters.html`.

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

[17] Center for Nonlinear Science, `www.cns.gatech.edu`.

[18] L. Vela-Arevalo and R.F. Fox, ”Semiclassical Analysis of Long Wavelength, Multiphoton Processes: The Rydberg Atom,” *Physical Review A* **69**, 063409 (2004). This paper has been selected by the Editor to appear in Virtual Journal of Ultrafast Science-July 2004, Volume 3, Issue 7.

[19] G.H. Goldsztein, ”Two-dimensional rigid polycrystals whose grains have one ductile direction,” *Proc. R. Soc. Lond. A.* **459**, 1949-1968 (2003).

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

[21] E. Harrell, J. Fleckinger and F. de Thélin, ”Asymptotics for solutions of some nonlinear partial differential equations on unbounded domains,” *Electronic Journal of Differential Equations* **77**, 1-14, (2001).

[22] T. Shepherd and R. Hernandez, ”Activated dynamics across stochastic aperiodic potentials,” T. Shepherd and R. Hernandez, *Journal of Physical Chemistry B* **106**, 8176-8181 (2002).

{bibitemCAK99 C.A. Klausmeier, "Regular and irregular patterns in semiarid vegetation," *Science* **284**, 1826-1828 (1999).

[23] M. Lopez, L.F. Kahn, and K.E. Kurtis, "Creep and Shrinkage of High Performance Lightweight Concrete," *J. ACI Materials*, in press (2004).

[24] P. J. Mucha, S.-Y. Tee, D. A. Weitz, B.I. Shraiman and M.P. Brenner "A model for velocity fluctuations in sedimentation," *Journal of Fluid Mechanics* **501**, 71-104 (2004).

[25] P. Dell'Aversana and G.P. Neitzel, "Behavior of noncoalescing and nonwetting drops in stable and marginally stable states," *Experiments in Fluids* **36**, 299-308 (2004).

[26] 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)

[27] L.A. Smith "What Might We Learn from Climate Forecasts?" *Proc. National Acad. Sci. USA* **4** (99): 2487-2492 (2002).

[28] L.H. Ting and J.M. Macpherson, "Ratio of Shear to Load Ground Reaction Force May Underlie the Directional Tuning of the Automatic Postural Response to Rotation and Translation," *Journal of Neurophysiology* **92** 808-823 (2004).

[29] E.O.Voit, *Computational Analysis of Biochemical Systems. A Practical Guide for Biochemists and Molecular Biologists*, xii + 530 pp., Cambridge University Press, Cambridge, U.K., (2000).

[30] 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).

[31] K. Wiesenfeld, T. Wellens, and A. Buchleitner "Lectures on Stochastic Resonance," pps. 107-138, Ch. 3 of the book *Coherent Evolution in Noisy Environments*, 107-138, A. Buchleitner and K. Hornberger, eds. Springer-Verlag, Berlin (2002).

[32] P.K. Yeung,S. Xu, and K.R. Sreenivasan, K.R. " Schmidt number effects on turbulent transport with uniform mean scalar gradient,"*Physics of Fluids* **14**, 4178-4191 (2002).

[33] R. Sadr, M. Yoda, Z. Zheng, and A.T. Conlisk, "An experimental study of electro-osmotic flow in rectangular microchannels," *Journal of Fluid Mechanics* **506**, 357-367 (2004).

[34] T. Hou, H. Kim, B. Rozovskii and H. M. Zhou, "Wiener Chaos Expansions and Numerical Solutions of Randomly Forced Equations of Fluid Mechanics," in the *proceedings to the 6th Hellenic European Conference on Computer Mathematics and its Applications*, Athens, Greece, Sept. 25-27 (2003). ⇓PRELIMINAR

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

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

[37] L.A. Bunimovich and J. Rehacek, "Nowhere dispersing 3d billiards with nonvanishing Lyapunov exponents," *Comm. Math. Phys.* **189**, 729 (1997).

[38] L.A. Bunimovich and J. Rehacek, "How high-dimensional stadia look like," *Comm. Math. Phys.* **197**, (1998).

[39] L.A. Bunimovich and J. Rehacek, "On the ergodicity of high-dimensional focusing billiards," *Ann. Inst. H. Poincare* **68**, (1998).

[40] T. Shepherd and R. Hernandez, "Chemical Reaction Dynamics with Stochastic Potentials Beyond the High-Friction Limit," *J. Chem. Phys.* **115**, 2430 (2001).

[41] L.A. Bunimovich, "Walks in Rigid Environments," *Physica* **A279**, 169 (2000).

[42] L.A. Bunimovich and M. Khlabystova, "Localization and Propagation in Random Lattices," *J. Stat. Phys.* **104**, 1155 (2001).

[43] A. L. Bertozzi and M. P. Brenner, "Linear stability and transient growth in driven contact lines," *Phys. Fluids* **9**, 530-539 (1997).

[44] S. J. VanHook, M. F. Schatz, J. B. Swift, W. D. McCormick, and H. L. Swinney, "Long-wavelength surface-tension-driven Bénard convection: experiment and theory," *J. Fluid Mech.* **345**, 45 (1997).

[45] M. F. Schatz and G. P. Neitzel, "Experiments on thermocapillary instabilities," *Annu. Rev. Fluid Mech.* **33**, 93 (2001).

[46] V. Petrov, M. F. Schatz, K. A. Muehlner, S. J. VanHook, W. D. McCormick, J. B. Swift, H. L. Swinney, "Nonlinear control of remote unstable states in a liquid bridge convection experiment," *Phys. Rev. Lett.* **77**, 3779-3782 (1996).

[47] R. Artuso, E. Aurell and P. Cvitanović, "Recycling of strange sets I: Cycle expansions," *Nonlinearity* **3**, 325 (1990).

[48] Y. Kuramoto and T. Tsuzuki, " Persistent propagation of concentration waves in dissipative media far from thermal equilibrium," *Progr. Theor. Physics* **55**, 365 (1976).
G.I. Sivashinsky, "Nonlinear analysis of hydrodynamical instability in laminar flames — I. Derivation of basic equations," *Acta Astr.* **4**, (1977) 1177.

[49] L.A. Bunimovich and Ya.G. Sinai, "Space-time chaos in coupled map lattices," *'Nonlinearity"* **1**, 491 (1988).

[50] L.A. Bunimovich and Ya.G. Sinai, "Statistical Mechanics of Coupled Map Lattices," pp. 167-187 in K.Kaneko, ed., *Coupled Map Lattices* (J.Wiley, New York 1993).

[51] see, *e.g.*, "The constructive role of noise in fluctuation driven transport and stochastic resonance", special focus issue of Chaos (volume 8), edited by R.D. Astumian and F. Moss (1998).

[52] R.F. Fox, "Rectified Brownian movement in molecular and cell biology", Phys. Rev. E **57**, 2177-2203

(1998); R.F. Fox and M.H. Choi, "Rectified Brownian motion and kinesin motion along microtubules," Phys. Rev. E **63**, 051901, 1-11 (2001).

[53] Georgia Tech Center for Education In Science Mathematics and Computing, `www.ceismc.gatech.edu`.

[54] Center for Computational Molecular Science & Technology, `www.ccmst.gatech.edu`.

[55] `www.cns.gatech.edu/CNS/Bylaws.html`.

[56] Analysis, Computation, and Experiment Lab, `www.ace.gatech.edu`.

[57] The Southeast Applied Analysis Center, `www.math.gatech.edu/saac`. ⇑PRELIMINAR
⇓PRELIMINAR

3 Five-Year Budget

[29]

4 Budget Justification

[30]

EVERYTHING FROM HERE TO sect. IS OF INSPIRATIONAL VALUE ONLY - WILL BE DROPPED FROM THE PREPROPOSAL:

[29] NSF requires: (uploaded as NSF Form 1030): A one page, five-year summary. Anticipated Funding Amount up to $2.95M per award over 5 years. Additional funding of international activities for some awards of up to $500K per award over 5 years.

[30] NSF requires: 1-page justification uploaded to NSF

[31] A unique aspect of nonlinear science is that research is driven by the flux of ideas across disciplinary boundaries. Given the essential role students at all levels play in conducting research, such flux is most effectively generated through the establishment of a **cross-disciplinary training program** integrating research, education, and training with the dual goals of attracting a wide range of undergraduate, graduate, and postdoctoral students to physics and providing them with a stimulating and thoroughly modern learning environment. To ensure the success of the program, a large fraction of the IGERT funded graduate students will be co-advised, with one advisor from student's home department and the other external, at least one of the advisors being a IGERT member. This arrangement will greatly assist in initiating new cross-disciplinary collaborations.

On the other hand, equipping students with skills that are cross-disciplinary, method based, rather than discipline specific, nonlinear science is uniquely positioned to **offer the students a broad, diverse education**, and prepare them for today's rapidly evolving professional environment. Coupled with the cross-disciplinary nature of IGERT, such training will meet the recommendation of the NRC report [1] to physics departments "to review and revise their curricula to ensure that they are engaging and effective for a wide range of students and that they make connections to other important areas of science and technology". In order to effectively achieve these goals, the proposed research and training programs will transcend departmental boundaries, differing from the conventional training model in a number of significant ways.

The success of the training program will crucially depend on the availability of the infrastructure that can only be created by a Center such as the proposed IGERT. The need for a strong foundation in the analysis of nonlinear dynamical systems is common to many research programs in science, engineering, and mathematics. At GT, courses on nonlinear dynamics [13] are currently taught in the mathematics and physics departments, each from a different perspective, and draw students from biomedical, chemical, aerospace, civil, electrical and mechanical engineering, materials science, and chemistry. While students would clearly benefit from a program based on a broad, coherent, and unified view of nonlinear science, college and school boundaries need

[31] **file** outreach.tex - Sep 9 2002

to be superseded by a framework that integrates what otherwise would be isolated collaborations between individual faculty members. The program built around the IGERT initiative will generate a new level of integration in graduate and post-graduate education by involving faculty in different departments in an effort to unify the nonlinear science curriculum across the participating schools. Equally important, combining the resources of the Center's MREs will make it possible to offer undergraduate level cross-disciplinary courses to students from participating institutions.

The core of the cross-disciplinary training program will consist of an **Introductory Nonlinear Science** course on the mathematical and computational techniques of nonlinear science followed by a rotating sequence of **Applications of Nonlinear Dynamics** courses based on the research interests of individual Center members and rounded out by a semester of **Special Topics in Nonlinear Science** featuring research on specific projects carried out by small teams supervised by faculty members with complementary expertise and perspectives. The level of courses will vary from advanced undergraduate to second year graduate, targeting the range of students that can be most effectively recruited into research programs. As one of the new initiatives, IGERT will offer an advanced web-based year-long gradute nonlinear course [7], which will play an important role in reaching and educating students at remote locations and attracting them to the program. The courses will gather all nonlinear science students in an activity that stresses commonalities among various fields, and it will provide a sense of intellectual community fundamental to the success of the program. The course work will require coordinated collaboration with peers and teachers from different backgrounds, helping students develop communication skills that will prove invaluable in future careers in industry or academia.

This training will equip young researchers with the tools and intuition needed to tackle complex nonlinear problems arising in many guises and various technical fields. In order to offer students a deep learning experience outside the Ph.D. thesis research, the educational core of the training program will be supplemented by the following important components. A **welcoming workshop/retreat**, before the start of each fall semester, will introduce the incoming young researchers to the IGERT. New students will pair up with a nonlinear science advisor, preferrably from outside their own department, who will oversee the student's progress during the first two years in tandem with the departmental advisor. An **Interdisciplinary Nonlinear Science Seminar** series [13], initiated in January 2001, has drawn a wide attendance from the participating departments and institutions. IGERT would enable us to run the seminar on an ongoing basis and to broaden its scope to engineering and biological applications. **Graduate Student Seminars** organized for and by the students will give them opportunity for public presentation of their own research in a supportive setting, engage them in mutually beneficial exchange of ideas, and generally enhance their communication skills; it will also provide a forum for directed discussions on ethics and conflict of interests in research. An active **visitor program** will help promote and maintain national, international, and industrial collaborations. Priority will be given to visitors whose research relates to that of participating IGERT faculty, and who demonstrate potential as external mentors to our graduate students and junior researchers. A **Regional Nonlinear Workshop**, a yearly cross-disciplinary meeting organized jointly with other Southeastern universities such as Duke, U. of Alabama, and U. of Florida, will expose students from regional universities to the forefront of research, and give them an opportunity to present their own work in poster sessions. **Joe Ford Fellowships**, named in honor of late GT Professor Joseph Ford, one of the pioneers of classical and quantum chaos, will sponsor several outstanding postdoctoral fellows each year. These Fellows, associated with the Center, rather than its individual members, will have complete freedom in choosing their research directions and serve as a glue between different research projects. In addition, by combining the resources of the Center, the Departments, and the Institute, the IGERT will be able to make competitive **graduate fellowship** offers to incoming graduates, making the program more attractive to a wider range of students. These fellowships will be primarily used to support co-advised students, covering the first two years during which students are normally supported as teaching assistants, allowing them to concentrate on the study and research in nonlinear science.

Joining the forces of the affiliated faculty and students is instrumental in making a coherent contribution to a number of outreach programs organized under the umbrella of the GT Center for Education Intergrating

Science, Mathematics, and Computing (CEISMC) [53] and targeted at the middle and high school students and teachers. For instance, participation in such programs as **FutureScape** and the NSF-sponsored **Integrating Gender Equity And Reform** (InGEAR) will help educate girls and young women about careers in nonlinear science, broaden their horizons and raise their aspirations by exposing them to careers they may not have contemplated otherwise. The Center will also actively participate in the new **Post-secondary Readiness Enrichment Program** (PREP) created by the University System of Georgia. This program addresses primarily the seventh grade and is designed to assist students and their parents in making timely, informed decisions that will adequately prepare young people for their higher education and career goals. The Center will also provide the foundation for continuing educating in the area of Nonlinear Science of those high school and middle school science and mathematics teachers enrolled in the year-round **Georgia Industrial Fellowships for Teachers** (GIFT) program, whose primary goal is to provide the exposure to the cutting edge research in the academic and industrial settings.

At the college level, following up on the success of the NSF Southeast Applied Analysis Center [57] outreach program, IGERT members will be sent to deliver lectures on various topics of modern physics, biology and mathematics as **Center Ambassadors** to Southeast region non-research educational institutions and historically black colleges and universities. IGERT will offer teaching reduction to the members who perform exceptionally as such lecturers, and implement a series of measures to aid recruitment and retention of students from under-represented groups, such as offering **Summer Internships for Minority Undergraduates**. Both GT Physics and GT Chemistry run highly successful NSF-funded **Research Experience for Undergraduates** (REU) programs, bringing some 30 gifted undergraduates to GT every summer, some of which are advised by the IGERT faculty. In summary, the goals of the IGERT outreach program are to bring the inspiration of cutting edge physics research to bright undergraduates, K-12 students, and teachers, to build bridges to faculty isolated at non-research institutions, and to inform talented students about the attractiveness of GT graduate programs.

The *assessment* of effectiveness of IGERT outreach program is detailed on p. **??**. **The assessment** of the program's success will rely on detailed feedback from students, internship hosts, participating faculty, long-term visitors, and thesis advisors. Annual assessments will concentrate on the performance of the IGERT J. Ford Fellows, student internships, MREs progress, Nonlinear Science Course, Nonlinear Science Seminar, Center Ambassador program, Visitor Program, and Regional Conference. Starting with the third year, the assessment will also involve the MREs research impact, recruitment, retention, PhD theses time-to-degree measures, publications, and a visit of an external expert committee.

The above range of activities, while highly desirable, cannot be sustained by the individual grants. The very existence of the proposed program hinges on the availability of cross-disciplinary funding, something that only IGERT can make possible.

[32]

Cross-disciplinary workshops, internships and other training initiatives will make use of the extensive connections the IGERT faculty has with other institutions and labs. We now provide a few examples of such cross-fertilization initiatives already in place. First, the already established **institutional cross-connections**:

- IGERT will collaborate intensively with the *NSF IGERT* programs at Northwestern [36], Cornell and U. of Arizona, as well as with a number of other leading centers for nonlinear science (check the Center webpage [15] for a complete list). The ties are particularly close to the Northwestern IGERT, originally led by P. Cvitanović.
- GT is one of the six university partners in the team which operates the *Oak Ridge National Laboratory* (ORNL), linking the lab to academic research. Geographically close, and with common interests in complex and nonlinear systems, GT IGERT and ORNL already plan several collaborative initiatives (detailed below).
- The IGERT fluid dynamics GT Physics & ME program [MS,RG,G.P. Nietzel] interacts the *Institute of Paper Sciences & Technology* (C. Aidun) housed at GT, where the fundamental problem of pattern formation is relevant to increased efficiency in coating of paper.
- GSB and KW have formed a "Hyperscanning Consortium" with colleagues at Baylor College of Medicine, Princeton University and Caltech, in order to perform synchronized MR scanning of people interacting with each other, and study brain patterns of interacting groups of humans.

Every IGERT faculty member has extensive external collaborations. Here we highlight a few examples of **cross-institutional research ties** that would be enhanced by the IGERT visitor, internship and workshop programs:

- KW and R. York (UC Santa Barbara, Electrical Eng.), T. Heath (GT Research Inst. staff scientist) -

[32]**file** national.tex - Oct 6 2004 version

Fast Dynamical Control of Antenna Arrays: Experiments at Santa Barbara are testing a new scheme for very fast manipulation of electromagnetic beams, scheme based on GT theoretical advances in understanding how synchronized nonlinear oscillators behave under variations of the element parameters.

- KW and F. Jaramillo (Carleton College, Biology) - *The role of noise in the auditory system*: The "stochastic resonance" experiments are being performed at Carleton College, and a model for the hair cell is under development at GT (see p. **??**).

[33]

Internships: We have contacted a number of potential hosts who have expressed their interest in participating in the internship program (see p. 55). Close contacts between the interns' advisors and hosts will contribute substantially to turning internships into full-fledged collaborations. To give a flavor of what we have in mind, we give here two examples of potential hosts and what they would offer. Others will be contacted on case by case basis, pending specific IGERT student or host research initiatives.

- *D. del-Castillo-Negrete, Oak Ridge National Laboratory.* Theorist, expert on the application of dynamical systems methods to the study of transport problems in fluids and plasmas, dynamics of many-body Hamiltonian systems with long range interactions, and pattern formation in reaction-diffusion systems, research interests shared with the IGERT faculty. GT and ORNL are already partners on the institutional level, with long experience of GT students working at ORNL.
- *R.E. Ecke and R. Mainieri, Los Alamos National Laboratory.* Experiments on pattern formation in fluids. Theory of nonlinear dynamics, statistical mechanics of chaotic systems. [34]

An internship at ORNL and LANL will provide a student with a unique opportunity to explore the research environment at a National Laboratory.

Workshops: IGERT plans a series of workshops. On the national level, IGERT will propose to host the

[33] PC: perhaps include PC, Mogul
[34] PC: add details

Dynamics Days 2005, the main US annual meeting in nonlinear science, possibly in collaboration with the Oak Ridge National Lab. The *Regional Nonlinear Workshop* (see p. 54) currently under preparation is

- **ORNL-IGERT Interdisciplinary Workshop on Transport**

  DATE: June 2003

  LOCATION: Oak Ridge National Laboratory

  ORGANIZERS: D. del-Castillo-Negrete (ORNL) and P. Cvitanović (IGERT)

  FUNDING: Shared ORNL/IGERT, with emphasis on graduate student stipends. 40 participants

  PROCEEDINGS: A focus issue of the CHAOS journal

  SPEAKERS: *(preliminary list) C. Jones (Brown, transport in oceanographic flows), R. Pierrehumbert (U. Chicago, transport in atmospheric flows), T. Tel (Eotvos U., Hungary, transport in chemical active flows), D. Astumian (U. of Maine, transport in biological systems), S. Wiggins (Bristol U., UK, transport in dynamical systems), R. Behringer (Duke, transport in granular flows), J. Gollub (Haveford College, experiments on transport), G. Zaslavsky (Courant Institute, NYU, transport in plasmas).*

  ABSTRACT: The study of transport is an important problem of common interest to many areas of science and technology including plasma physics, biology, chemistry, oceanography, atmospheric sciences, engineering, and dynamical systems. The goal of this cross-disciplinary workshop is to bring together experts from these areas for a discussion of nonlinear dynamics and complex systems techniques in the study of transport.

IGERT academic environment: No less important than ties to other institutions is the immediate context in which IGERT will operate. The overriding concern in setting up the Center structure (see sect. **??**) is ensuring sufficient fluidity in faculty composition to enable us to recruit new talent into IGERT as new cross-disciplinary research directions open up. GT and EU provide rich intellectual environment which will greatly enhance IGERT effectiveness as a platform for cross-disciplinary interactions. GT School of Mathematics CDSNS [35] contributes excellent visiting researchers, seminars, and training opportunities in mathematical methods for nonlinear science. [35] To name but a few, preeminent scientists such as E. Carlen, M. Loss (GT mathematical physics group), K. Mischaikow (GT Mathematics / director CDSNS), W. Gangbo (GT Mathematics / CDSNS), M. Borodovsky (GT Biomathematics), D. Dusenbery, R. Wartel (GT Biology), G. Hentschel and F. Family (EU Physics), and N. Chernov and N. Simanyi (U. Alabama Mathematics, Birmingham) will interact with IGERT faculty and visitors. These excellent researchers could have equally well already been listed as IGERT faculty, and they and others in Atlanta area will be inducted if new research directions merit their joining IGERT.

[35] EMH: The GT has a long-standing record in the area. The CDSNS established 1988. GG, EMH and PM from the proposal are associated faculty of CDSNS.

RY

[36]

.1 International collaborations

IGERT international collaboration program consists of organizing international workshops, hosting senior visitors and interns from outside of US and a foreigh internship program for IGERT students.

IGERT plans to co-organize a number of international workshops. IGERT faculty already has a lot of experience in organizing international conferences, workshops and symposia at Georgia Tech (the examples include e.g., Dynamics Days, Int-l conferences in Mathematical Physics and PDEs, etc.". Several IGERT faculty members were part of organizing committees of international conferences in US and overseas. P.Cvitanovic has organized and co-organized since 1981 about thirty conferences, workshops and schools in Europe and US, and has a well established international partner network. Other IGERT faculty members have also their international partners/collaborators networks, sometimes quite extensive ones. Workshops that IGERT is planing to organize wil be devoted either to new emerging areas of nonlinear science or will be quite interdisciplinary reflecting a broad interdisciplinarity of the body of IGERT faculty. Not all such workshops will be held in GaTech (and even in US). A few IGERT faculty members were approached by the directors of several international centers/institutes abroad asking to organize international workshops there. IGERT will be an exellent opportunuity to combine such meeting with a farther training/education of IGERT students. Internationally, some fifteen Sister Nonlinear Centers located in Argentina, Austria, Chile, Denmark, Germany, Hungary, Israel, Italy, Mexico, Netherlands, United Kingdom are IGERTs potential partners in organizing workshops, exchanging researchers, and hosting interns (for a complete list, please check the CNS webpage .

A few examples:

International Center of Theoretical Physics (ITCP), Trieste, Italy (Director Prof. Srinivasan) is one

[36] **file** international.tex - Oct 6 2004 version - npuBeT BaIIIuM

of the major international (and perhaps the largest) centers in Theoretical Physics. ITCP is a venue for many international meetings (including biannual Summer School in Dynamical Systems). ITCP hosts a large body of visitors and has several very strong and vibrant research groups. IGERT faculty has many common research interests with permanent faculty in ICTP. Especially hydrodynamics became after appointment of Srinivasan as director one of the focuse 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 ITCP.

Max Planck Institute for the Physics of Complex Systems, 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, with extensive workshop, visitor, postdoctoral and exchange program. MPIPCS is establishing now a PhD program where IGERT interns will be even able to get a formal credit (in US equivalent) for attending these courses during their internship.

Center for Chaos and Turbulent Studies (CATS), Copenhagen, Denmark, (Director Prof.Jense)n. 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, and CATS will host IGERT researchers and interns. IGERT will host Danish Research Academy (Danish PhD 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), Director Prof. Tomita. IAB, hosted by Keio University, Japan, is a leading world (and the leading in Asia) center in bioinformatics, computational and systems biology. The scientists in IAB are using ideas and methods of nonlinear science as major tools for modeling and simulations of the whole cell, analysis of gene networks and protein interactions. Some IGERT faculty (E.Voit) already have close working connections with IAB. Bioinformatics and Bioengineering are the main research efforts at GaTech. Many of IGERT faculty are working in these areas. It is fully expected that several IGERT faculty will visit IAB and start fruitful collaborations (as well as continue already existing ones) and that IAB will become one of the central places for the IGERT internship program

It is expected that IGERT students will complete a semester of internship in one of research centers abroad. The goal is to significantly broaden and strendthen education of IGERT students and provide young researchers with additional cross-disciplinary perspectives by exposing them to different experimental, computational, and theoretical approaches, using the expertise not available at GT/US. 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 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 finding new areas of opportunuity. It is expected that the internship program for IGERT students 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. A brief proposal will then be written that clearly states the goals of the internship, which is expected to last from three to six months and possibly form the basis for a publication. The internships will be reviewed after the first three months by the IGERT Executive Committee and home institution advisors to determine whether progress is sufficient to warrant an extension. The trainee will present her/his results in the Graduate Seminar Series, and, upon returning to the home institution, in the form of a written report.

To conclude, IGERT protocol (four supporting letters, five faculty, two pages) does not allow to fully describe the strength of already existing international collaborations and networks of IGERT faculty at Georgia Tech. Additional relevant information can be found at the Center of Nonlinear Science webpage and at the individual webpages of IGERT faculty.

——————- OLD TEXT FROM 2002 ——————————————

IGERT plans to co-organize a number of international workshops. P. Cvitanović is the *Secretary of the*

European Dynamics Days Governing Board, a *Honorary Chair of the Let's Face Chaos* conference (Maribor, Slovenia May 2002), and a member of other international conference committees. Since 1981 he has organized or co-organized more than 25 conferences, workshops and schools in Europe and US, and has a well established international partner network. Internationally, some fifteen *"Sister Nonlinear Science Centers"* located in Mexico, Germany, Denmark, United Kingdom, Italy, Israel, Argentina, Hungary, Chile and Austria are IGERT's potential partners in organizing workshops, exchanging researchers, and hosting interns (for a complete list, please check the Center webpage [14]). A few examples:

- *Center for Chaos and Turbulence Studies* [16] - M.H. Jensen, director. A leading European center in physics of complex systems ranging from neuronal activity to quantum chaos, housed at the Niels Bohr Institute, Danish Technical University, and Nordita, Copenhagen. CATS will host IGERT researchers and interns. IGERT will host the Danish Research Academy *Danish Ph.D. School in Nonlinear Science* supported students and visitors. As many European Ph.D. programs require research training abroad, these and other similar exchanges will be very beneficial to the overall IGERT recruiting effort.
- *Centro Internacional de Ciencias*, Cuernavaca, Mexico - T.H. Seligman, director. Promotes scientific exchange, with particularly strong Latin American visitor and conference program. IGERT and CIC have a tentative agreement to co-organize two "pan-American" workshops, the first one on "Classical and quantum chaos in few- and many-body systems" in winter 2004 and the the second one in winter of 2006.
- *Max Planck Institute for the Physics of Complex Systems*, Dresden - H. Kantz, Head, Nonlinear dynamics and time series analysis group. The main European meeting ground for young researchers and leading international scientists in physics of complex systems, with intensive workshop, visitor, postdoctoral and exchange program. Collaboration with IGERT desired in order to strengthen ties to US.

In addition - the space allotted does not allow a detailed listing - each individual IGERT faculty member maintains **international research ties** that will enhance and be enhanced by the IGERT visitor, internship and workshop programs.

- LAB and Ruedi Stoop, Institute of Neuroinformatics, ETH/Univ. of Zuerich, experimental, numerical and theoretical studies of systems of neocortical neurons
- LAB and Mikhael Blank, Institute for Information Transmission Problems, Moscow, Russian Ac. Sci.,dynamics of multi- component systems (deterministic and stochastic) and their phase transitions
- LAB and Carlo Boldrighini, Univ.di Roma 1, Dept. of Math. transport coefficients, long tails in models of statistical physics and in dynamical systems

RY

[37] It is the very essence of nonlinear science that the same researchers contribute to widely different fields, here split into different MREs. Research advances in nonlinear science are inseparable from the training it offers, and that is the core effort that all IGERT participants will contribute to: Integration of the research, educational, and training with the dual goals of attracting a wide range of undergraduate, graduate, and postdoctoral associates to physics and providing them with a stimulating and thoroughly modern learning environment. In equipping the students with skills that are cross-disciplinary, method based, rather than discipline specific, nonlinear science is uniquely positioned to offer the students a broad, diverse education, and prepare them for today's rapidly evolving professional environment. Coupled with the cross-disciplinary nature of IGERT, the training offered will meet the recommendation of the NRC report to physics departments "to review and revise their curricula to ensure that they are engaging and effective for a wide range of students and that they make connections to other important areas of science and technology". In order to effectively achieve these goals, a number of novel **cross-cutting methodologies** for education and training will be developed. The proposed research and training will transcend departmental boundaries, differing from the conventional model of disciplinary education in a number of significant ways.

The need for a strong foundation in the analysis of nonlinear dynamical systems is common to many research programs in science, engineering, and mathematics. At GT, courses on nonlinear dynamics are currently taught in the mathematics and physics departments, each from a different perspective, and draw students from biomedical, chemical, aerospace, electrical, and mechanical engineering, materials science, and chemistry. (For a current listing of courses, seminar series, workshops, and other activities, consult the Center webpage [13]). While students would clearly benefit from a program based on a broad, coherent, and unified view of nonlinear science, college and school boundaries need to be superseded by a framework that integrates what otherwise would be isolated collaborations between individual faculty members. The program built around the IGERT initiative will generate a new level of integration in graduate and post-graduate education by involving faculty in different departments in an effort to unify the nonlinear science curriculum across

[37]**file** school.tex - Aug 10 2001, printed October 9, 2004

the participating schools. Equally important, combining the resources of the Center's MREs will make it possible to offer undergraduate level cross-disciplinary courses to students from participating institutions.

The core of the cross-disciplinary training program will consist of an **Introductory Nonlinear Science** course on the mathematical and computational techniques of nonlinear science followed by a rotating sequence of **Applications of Nonlinear Dynamics** courses based on the research interests of individual Center members and rounded up by a semester of **Special Topics in Nonlinear Science** featuring research on specific projects carried out by small teams supervised by faculty members with complementary expertise and perspectives. The level of courses will vary from advanced undergraduate to second year graduate, targeting the range of students that can be most effectively recruited into research programs. As one of the new initiatives, IGERT will offer an advanced web based year-long graduate course [7]. The courses will gather all nonlinear science students in an activity that stresses commonalities among various fields, and it will provide a sense of intellectual community fundamental to the success of the program. The course work will require coordinated collaboration with peers and teachers from different backgrounds, helping students develop communication skills that will prove invaluable in future careers in industry or academia.

This training will equip young researchers with the tools and intuition needed to tackle complex nonlinear problems arising in many guises and various technical fields. In order to offer students a deep learning experience outside the Ph.D. thesis research, the educational core of the IGERT training program will be supplemented by the following important components:

Internships at other institutions, such as external academic, government, or industrial research centers will provide young researchers with additional cross-disciplinary perspectives by exposing them to different experimental, computational, and theoretical approaches, using the expertise not available at GT/EU, as well as forging new collaborations.

The above range of activities, while highly desirable, cannot be sustained by the individual grants. The very existence of proposed program hinges on the availability of cross-disciplinary funding, something that only IGERT can make possible.

Our plans for recruiting graduate students to the proposed IGERT program build on the existing graduate recruitment efforts of the individual departments. The students will enroll in one of the following Ph.D. programs associated with the participating departments: Biomedical Engineering, Chemical Engineering, Electrical and Computer Engineering, Engineering Sciences and Applied Mathematics, Materials Science and Engineering, Mathematics, Mechanical Engineering, Physicas and Astronomy, and the Neuroscience.

[38]

We propose to recruit approximately seven new Ph.D. students to the IGERT program each year, with fellowship offers that cover the first two years of graduate study. Experience with recruiting graduate students to our individual departments indicate that multiple-year fellowship offers are extremely attractive to prospective students. Such fellowships give students freedom to focus on their studies, and also to choose their thesis topic and advisors with less focus on faculty funding situations. In many instances the fellowhip offers will combine IGERT funding with existing departmental and University fellowships; most of the participating departments already offer prospective graduate students nine-month fellowships for the first year of study. By combining resources, we will be able to make more competitive fellowship offers (*e.g.* \$19-\$20K/year), and also to offer some continued funding to more senior IGERT program graduate students who have begun cross-disciplinary thesis research. Such extensions of funding will be made on a competitive basis; see section **??** for details of fellowship resource allocation. Student retention will be facilitated by a close student-program advisor relationship that is established as soon as the student arrives at GT and continues until the student completes the Ph.D. (see section **??**.**??**).

The program will be advertised in three primary ways: (1) through the participating departments graduate program brochures and webpages, as well as on the GT Nonlinear Science webpage `www.cns.gatech.edu`, (2) by the participating faculty contacting colleagues at other academic institutions to alert them to the new program, (3) by announcements posted at research conferences, in nonlinear dynamics electronic newslet-

[38]PC: insert?: the Nonlinear Science Program offers to students funded by IGERT a minor in Nonlinear Science, harmonized with their departmental requirements. Such broadening of student's Ph.D. profile should significantly improve employment prospects.

ters, and in newsletters aimed at minority and women scientists, mathematicians, and engineers (*e.g.* the Association for Women in Mathematics Newsletter), and (4) by targeted contact and/or visits by participating faculty members to relevant summer undergraduate research programs, in particular those enrolled by minority students. Prospective candidates will be invited to visit GT, where a graduate student already in the program will serve as a host, and where they will meet the faculty and other students in the IGERT.

In addition to these general recruiting strategies, IGERT funding will enable us to implement the following measures to aid recruitment and retention of students from under-represented groups:

- **Summer Internships for Minority and Women Undergraduates**

  We propose to offer 3 summer internships per year to promising women and/or minority undergraduates for the summer between their junior and senior year. Each student will be paired up to work with one of the IGERT faculty, either by assisting in a lab, implementing numerical computations, or working on a small-scale research project with the first year graduate students in the IGERT program. Many of the participating IGERT faculty have considerable experience directing undergraduate honors thesis research projects, as well as guiding undergraduates in summer research projects *e.g.* as part of NSF's REU program (see section **??**). Each undergraduate will be assigned a IGERT graduate student who will serve as a "junior mentor". Minority students will also participate in the activities of GT's summer "Minority Research Opportunity Program"[39] which will provide them with an additional network of peers.

  The goal of the internship is two-fold: the participating students benefit from exposure to nonlinear science research and graduate student life at the critical time in their education, and the IGERT benefits by establishing a relationship with strong prospective graduate students.

[39]PC: this program is not GT, it is Northwestern

[40]

The unique position of nonlinear science lying on the interface of two or three different disciplines is reflected in the funding patterns specific to cross-disciplinary research: although established research programs have somewhat broader funding opportunities, it is substantially more difficult to find individual funding opportunitities for new research directions, since typically they will not be given priority by either of the core disciplines. This puts special emphasis on the availability of **seed funding in emerging areas**, especially high-risk ones.

The IGERT will be able to provide such funding quickly and in an extremely flexible way. The highest priority will be given to collaborative research lying on the interface of different disciplines and involving faculty from different departments. Second priority will be assigned to joint research by the faculty members in the same department or discipline. In both cases at least one of the investigators will come from the IGERT faculty. In general, the goal of seed funding will be to initiate and stimulate preliminary research in the novel and promising areas of opportunity, where no existing patterns of funding exist. Once the potential of a given direction is proven at the preliminary stage, individual and/or group funding from more conventional sources will be sought.

The availability of seed funds will be especially critical for the success of **junior faculty members** who typically do not have other sources of funding which can be used to initiate new research directions. The criteria and mechanisms for selecting and evaluating projects are addressed in sect. **??**. Given the difficulties that even senior faculty members face in funding new research directions, this task becomes especially and unnecessarily complicated for junior faculty, who do not yet have a track record of successful research to warrant favorable consideration by the granting agencies. Providing junior faculty with such flexible funding will save a lot of time required otherwise to prepare, submit, and undergo a review of several full-scale exploratory proposals, enabling the junior faculty to concentrate instead on the proposed research. All of this is especially true where nonlinear science with its cross-disciplinary focus is concerned.

[40] **file** emerging.tex - Sep 9 2002

As was repeatedly stressed throughout this proposal, a distinguished feature of nonlinear science is that it is driven by cross-pollination of ideas between different disciplines as well as between different fields within natural sciences, engineering and medicine. As a means to promote such cross-pollination, IGERT will organize and host a series of bi-annual **Applied Nonlinear Science Workshops**, bringing together IGERT faculty and students and researchers from regional universities, national laboratories, and industrial research centers. Each year the workshops will target a different application area (e.g., neural dynamics, control of extended systems, plasma physics, biological excitable systems, etc.), fostering collaborations and transfer of ideas, creating new approaches, and stimulating new research directions by bringing together specialists with complementary research expertise.

Organization of such workshops depends crucially on the availability of centralized funding and infrastructure. On the other hand, by limiting the scope of the meeting and bringing together a sharply focused group of researchers, such meetings will play a role that neither the individual contacts nor the very broad international conferences such as the SIAM Snowbird meeting play. The workshops will serve the dual purposes of disseminating the methodology developed by the nonlinear community to other fields with the latter providing the focus for the research directions in the nonlinear science and, at the same time, establishing new collaborations between members of different institutions.

Complementing the above research-oriented activities will be a range of education-oriented activities, such as a Regional Nonlinear Workshop, internship support for outstanding students, and the development of a web-based nonlinear courses, all of which are expected to have a strong impact on the research component.

The **Regional Nonlinear Workshop** will differ significantly from the Applied Nonlinear Science Workshop in that it will be oriented primarily towards students of all levels. Scheduled yearly, this cross-disciplinary meeting will be organized jointly with other Southeastern universities such as Duke, U. of Alabama, and U. of Florida, it will be hosted on an alternating basis by the IGERT and the fellow institutions. The main goal of the workshop will be to expose students from regional universities to the forefront of research, and give them an opportunity to present their own work in poster sessions. This workshop will have a broader scope, encompassing the whole field of nonlinear science. This broad scope will give the students the sense of diversity and at the same time closeness of the nonlinear science community, highlighting the many existing and prospective links between different directions pursued by different research groups.

IGERT will offer to students and post-doctoral fellows of exceptional promise (either from IGERT, or from outside) **internship support**, the goal of which is to significantly broaden and strengthen their education and provide young researchers with additional cross-disciplinary perspectives by exposing them to different experimental, computational, and theoretical approaches, using the expertise not available at GT/EU. 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 to this, the internship program will play an instrumental role in forging new collaborations and finding new areas of opportunity.

The trainee, aided by the home institution advisor, will make the initial contact with the internship advisor. A brief proposal will then be written that clearly states the goals of the internship, which is expected to last 3-6 months and possibly form the basis for a publication. The internships will be reviewed after the first three months by the IGERT and home institution advisors to determine whether progress is sufficient to warrant an extension. The trainee will present his/her results in the Graduate Seminar Series, and, upon returning to the home institution, in the form of a written report.

Yet another component of the educational activity of the center, and an integral part of its outreach program, a **web-based nonlinear course** will play an important role in reaching and attracting students from remote locations, providing them with the inside look at the current research topics in classical and quantum chaos. Such course could be based on the ChaosBook [7], a hyperlinked web-based course currently under design by P. Cvitanović and coauthors, a novel and unique approach to teaching an advanced graduate level nonliner physics course. In addition to the extremely valuable potential of accessing the broadest possible audience, the major advantage of a web-based course compared to a textbook-based course is a unique opportunity to incorporate the dynamical aspects into the presentation. Such dynamical aspects realized through animations, java applets, interactive scripts, and so on, can only be implemented with a considerable investment of time and resources. Given the scope of the material, this will require involvement of a group of advanced undergraduate and/or graduate students for an extended period of time. Although clearly innovative and beneficial for the whole nonlinear science community, such a project cannot be supported by any individual grant and requires a centralized approach.

Reviewer Information

[41] ⇑PRELIMINAR

[41] NSF requires: (THIS PART UPLOADED SEPARATELY TO NSF) - Enter the following information into the FastLane "List of Suggested Reviewers" form: (1) a list of individuals (and their affiliations) outside the participating institutions whose participation in the review of the full proposal might constitute a conflict-of-interest through association with the participants, and (2) a list of individuals who are suitable to serve as impartial reviewers.