3 Physics Frontier Center in Nonlinear Science

A Vision

The impact of nonlinear science across the broad spectrum of natural, life, and medical sciences is due to the unity of its fundamental concepts. Since the renowned nonlinear dynamics program at GT is located at one of the country's leading engineering schools, and in close proximity to Emory, one of country's most eminent medical schools, we are in a unique position to respond to the challenge posed by the complex systems found in engineering and materials, life and medical sciences – recently identified by the National Research Council as one of the six grand challenges for physics. We propose to establish a cross-disciplinary *Physics Frontier Center in Nonlinear Science* (PFCNS) which will bring together faculty, researchers and students in basic sciences, engineering, medical sciences. We envision:

Cross-cutting MRCs, with nonlinear science as the unifying theme: The PFCNS cross-disciplinary program will be based on common concepts unifying a broad range of problems of basic science, such as pattern formation, non-equilibrium dynamics, turbulence, classical and quantum chaos. Research and advanced training fostered by PFCNS will impact on a diverse range of applications of nonlinear science to fields such as biophysics, neuroscience, engineering problems involving liquids, interface motion, novel materials, flows at nanoscales, and nonlinear control.

Training in cross-cutting methodologies: Nonlinear science provides the student with a set of common tools and methods to formulate and solve diverse problems, wherever they might arise: science, engineering, medicine, finance. PFCNS will stimulate cross-disciplinary research and communication skills through intensive project based courses, in which small teams investigate topics guided by faculty members with complementary perspectives. Furthermore, PFCNS supported cross-departmental research seminars and student-run seminars, regional workshops, yearly retreats, and an active visitor program will generate a highly cooperative and diverse research environment.

Strategic impact and outreach: *Why should PFCNS be based at Georgia Tech?* GT is the leading science and technology institution in the Southeast, with strong state and industrial support. It is a first rate engineering school, in process of rapid growth, with PFCNS profiting from the ongoing expansion of the GT/EU biomedical engineering, nanosciences, and biosciences. The PFCNS graduate training and research program will provide a unique common platform bringing together faculty and students across discipline boundaries, establish bridges to other research institutions in the Southeast, offer outreach to teaching, minority and industrial sites, and stimulate progress in the field nationally and internationally through a visitor program, exchanges and focused workshops. GT's location in Atlanta Midtown, with quick access to one of the world's best airports, makes it ideal for visitors and workshops, and it traditionally serves as a meeting place for researchers from universities in the South, as well as a site for major international conferences.

B Prior NSF support

Two prior NSF center grants form the basis for the current Center proposal:
P. Cvitanović, PI (until moving to Georgia Tech) - **IGERT #9987577**: Northwestern University *Dynamics of Complex Systems in Science and Engineering* (2000-2004). PFCNS would strongly interact with this "sister" program as well as with the Arizona and Cornell IGERT programs.
L.A. Bunimovich, CoPI and Director - **GIG #9632032**: *Southeast Applied Analysis Center* (1996-2001) has been very successful in establishing regional educational initiatives which PFCNS intends to extend and build upon.

Members of PFCNS faculty are PIs on the following individual NSF grants:
M. Schatz - CTS #9876590: *Control of Spatiotemporal Chaos in Thermal Convection*
L.A. Bunimovich - DMS #997215: *Dynamics and Kinetics*
R. Ghrist – DMS #9971629: *The Topology of Hydrodynamics*
J. Geronimo - DMS #9970613: *Some problems in orthogonal polynomials and wavelets*
S.P. DeWeerth - BES #9872759; IBN #951172: *A VLSI Model of Muscular Mechanics, Architecture, and Control*
R.F. Fox - MP #9819646: *Stochastic and Nonlinear Phenomena in Physics and Biology*
R. Hernandez - CHE #9703372: *Reaction Dynamics of Polymerization and a Computer-Enhanced Dialectic in the Physical Chemistry Curriculum*
T. Uzer - PHY #0099372: *Rydberg Electron Dynamics in External Fields*
T. Uzer - CHE #9803602: *Rydberg State Dynamics in Atoms and Molecules*

C Major Research Components

We highlight here the Major Research Components (MRCs) of the Center, and the ways in which they are interconnected. Throughout the text, the contributing faculty (see Sect. 4) are indicated by initials; [LAB] stands for L.A. Bunimovich, and so on.

C.1 Chaos in classical and quantum systems

GT has been at the forefront of classical and quantum chaos research since the very inception of the field, pioneered by (among others) GT researchers J. Ford, L.A. Bunimovich and P. Cvitanović. Current GT research is concentrated on the basic mechanisms of chaos in Hamiltonian systems and chaos-order transitions in finite and infinite-dimensional systems.

GT boasts of several world-renowned researchers in the areas of **ergodic theory**, **statistics** and **transport in dynamical systems**. Their research ranges from proofs of existence and non-degeneracy of transport coefficients in classical models of statistical mechanics to the development of realistic new models of complex physical systems. One of the central problems is the rate of **convergence to equilibrium**, both in conservative and dissipative (nonequilibrium) systems. GT mathematicians contribute perspectives from **braid**

theory to understanding of closed orbits of flows and periodic orbits of low dimensional systems [1, 2], and from geometrical and dynamical problems connected with geodesics of generalized billiards [3]. The **periodic orbit theory** [4] applies these deep mathematical results to physical problems such as **far-from-equilibrium transport**, conductance of mesoscopic devices, and the **semi-classical quantization** of classically chaotic systems [5].

GT researchers have also pioneered applications of dynamical systems theory to problems of operations research and robotics [6], applications which proved to be surprisingly efficient in factory settings. [LAB,PC,RWG]

GT is a leader in research on "Rydberg" atoms, in which an electron is promoted to such a high energy state that it almost becomes a classical object. These atomic laboratories for **quantum chaos** have been a source for significant discoveries, including stochastic ionization by microwaves. Here the Klauder coherent state formalism sheds new light on the quantum-classical correspondence, with the classical Lyapunov exponent acting as a quantum signature of classical chaos [7]. Theory with two or fewer degrees of freedom sufficed to interpret the early experiments, but not the current experiments which are breaking new ground in the dynamics of **multidimensional chaotic systems** and call for new diagnostic tools and new computational methods. [TU,RF]

Wavelet methods in time-frequency domain show great potential both as a diagnostic of chaos in higher dimensions and a promising new tool for numerical analysis. **Multiwavelets**, constructed from several basis functions, allow for closed-form wavelet formulas and facilitate numerical analysis of fluid mechanics problems such as the Stokes problem [8]. [TU,JG].

The cross-disciplinary team brought together by PFCNS will attack a number of experimentally measurable manifestations of quantum chaos where traditional approaches fail: **stochastic ionization** in rotating microwave fields [9] and **chaotic scattering** of electrons [10]. Recently developed phase-space transition state theory [11] will be applied to diverse problems, ranging from the rearrangements of atomic nanoclusters, **ballistic electron transport** through microjunctions, diffusion jumps in solids, to the **capture of comets and asteroids**. [PC,RF,TU]

Ongoing EU/GT investigations of **nonstationary dynamics in complex materials** are advancing understanding of diverse processes ranging from protein folding and polymerization to the flow of foams, colloidal suspensions, and granular materials. In some cases, the dynamics of reduced-dimension coordinates describing an effective solute may induce nonlinear responses in the effective solvent. In **spatially heterogeneous solvents**, models have been developed using the generalized Langevin equations with space-dependent friction. When the solute is sufficiently concentrated, the collective solute dynamics can be modelled by a time-dependent self-consistent friction [12, 13]. In situations described by recent theories of jammed materials, the existence of universal microscopic features [14] is hypothesized but, as yet, has not been observed in experiments. Confocal microscopy is being used to study the microscopic details of such materials in both static and dynamic settings [15, 16]. [RH,RF,EW]

Many physical problems are **hybrid systems**, which are neither purely deterministic nor purely random but rather share both of these features. This holds for disordered systems, chemical kinetics, and theoretical problems of computer science (Turing machines with many heads and/or many tapes). The time evolution of such systems is often quite counter-intuitive [17]. The requisite theory is of great interest for **collision-based computing**, a new and rapidly developing area of computer science. [LAB]

C.2 Dynamics of spatially extended systems

To date, the lion's share of progress in nonlinear physics has been made in the study of systems for which the asymptotic behavior can be understood in terms of a small number of coupled nonlinear ordinary differential equations (ODEs). However, physical problems involving dynamics of fields and flows (e.g., turbulence in industrial, atmospheric, and astronomical settings) or interconnected discrete media (e.g., integrated circuits, neural dynamics) have many degrees of freedom described by either large numbers of coupled ODEs or sets of partial differential equations (PDEs). One of the most daunting challenges facing nonlinear science today is the characterization of universal complex behaviors in such high-dimensional systems. Work at GT toward this goal is focused on four major areas: coupled arrays, pattern formation, spatiotemporal chaos (STC), and control of spatially extended systems.

When a large number of simple nonlinear elements are joined together in **coupled arrays**, the composite system can exhibit collective behaviors that are qualitatively different from behaviors of single elements [18]. If the individual elements are oscillatory, characterization of the phase and amplitude relationships between the oscillators becomes important, particularly for synchronized states. When the individual elements exhibit relaxational dynamics, the composite system can show complex avalanching behavior (first demonstrated in KW's pioneering paper [19]) known broadly as "self-organized criticality" (SOC). Present research focuses on the behavior of coupled arrays in applied physics. Work on **antenna arrays** (in collaboration with experimentalists at UCSB) is inspiring investigation of a new dynamical scheme for fast beam scanning and spatial beam shaping [20]. Studies of high frequency tunable electromagnetic generators (e.g., superconducting Josephson junctions) aim to include distributed electrodynamical effects that are not captured by traditional models based on arrays of locally coupled ODEs. Investigation of flux creep (**magnetic avalanching**) in granular superconductors is being explored as a candidate system for understanding general SOC-like behavior, as cellular automata models of magnetic avalanching can be directly related to the underlying physics described in terms of coupled ODEs [KW].

A rich variety of spatial structures arise in many dissipative systems out of thermodynamic equilibrium. The nonlinear aspects of **pattern formation** are described by bifurcation theory, which describes how qualitative changes in patterns arise when one spatial structure becomes unstable and is replaced by another. This approach becomes even more powerful when transitions are viewed as examples of spontaneous symmetry breaking, combining bifurcation theory with group theoretic symmetry analysis. Current efforts are focused on investigations of hydrodynamic systems, due to their several significant advantages: the basic equations are well posed and well understood, permitting extensive analytical and theoretical work that can be compared directly to highly quantitative measurements in well controlled experimental systems. GT studies focus on instabilities in fluid convection as well as instabilities associated with moving contact lines in the driven spreading of thin liquid films [22, 23]. Experiments conducted in MS's laboratory have the unique capability of both multipoint measurement and multipoint manipulation of flow dynamics by optical means, making possible direct measurements of stability of ideal patterns, studies of defect dynamics, and pattern control [24]. [MS, RG]

Accurate description of the dynamics is crucial for a number of practical and theoretical problems involving nonequilibrium systems, such as calculation of transport coefficients or control of unstable patterns. Due to the intrinsic nonlinearities and high dimensionality, analytic description of **spatiotemporally chaotic dynamics** is in general impossible. The tools of statistical mechanics and low-dimensional dynamical systems theory are not directly applicable either; a whole new approach to characterization of STC needs to be developed. The main idea of such an approach is based on the fact that, due to natural dissipation, only a relatively small number of degrees of freedom are active, such that asymptotically the dynamics is confined to a finite-dimensional invariant manifold. The two main goals of GT research in STC are to identify the relevant degrees of freedom and to construct a dynamically and statistically accurate description. Symmetry analysis reduces the problem dimensionality by factoring out the degeneracies associated with spatial invariance. A related study focuses on generic localized spatiotemporal instabilities to develop novel ways to extract relevant information from experimental data. Another direction involves generalization of the periodic orbit theory (Sect. C.1) to permit prediction of the long-time averages of dynamical observables for spatially extended systems [25]. [RG, PC]

Similarly to the studies of chaos, control theory has traditionally been focused on low-dimensional systems and progress in **control of spatially extended systems** to date has been mostly limited to the purely mathematical theory of optimal control of PDEs. In proposed research, the emphasis will shift toward developing a theory for controlling the dynamics of physically realistic systems. The concept of symmetries and group theoretic approaches here proves especially fruitful, linking the geometry to the dynamics [26, 27]. The present research concentrates on developing a practical control theory for extended systems. In particular, the theoretical effort relies on group theoretic techniques to address such geometrical issues as the role of boundary conditions in control of weakly confined systems, the effects of finite spatial resolution in sensing and actuation, the limits of distributed control using sparse arrays of sensors/actuators [28], and reduced-order description of infinite-dimensional dynamics as a way to naturally incorporate geometric information into the model. Other practical issues include the effects of unidirectional actuation on control. These approaches are being tested experimentally on several types of fluid-dynamic instabilities. [RG, MS]

C.3 Nonlinear dynamics in biology

The cross-disciplinary nature of the Center offers excellent opportunities in selected areas of biology and biophysics. Our combined effort will bring together researchers from GT and EUSM biology, physics, mathematics, and biomedical engineering departments. The neuroscience work will span the range from the subcellular, single cell, inter-neuronal to whole-brain levels. The common thread that these phenomena share is their dynamical behavior which is complex, often chaotic and always also stochastic. All areas described here combine experimental and theoretical components.

The interplay of **stochasticity and nonlinear dynamics** leads to important physical and biological effects. One such effect is the **rectified Brownian motion** underlying the functioning of molecular motors, such as the kinesin motion along microtubules. A larger issue is that rectified Brownian motion potentially provides a unified mechanism for a great many basic cellular processes, whereby metabolic Gibbs free energy can be converted into mechanical work [29]. [RF]

Another fundamental noise driven effect is **stochastic resonance** (SR), in which detection of weak signals is - counter-intuitively - enhanced by the presence of noise [30]. In collaboration with an experimentalist at Carleton College, KW is testing whether SR plays a functional role in hearing at level of individual hair cells. In vitro experiments show that SR occurs at noise levels comparable to the inherent Brownian motion of hair bundles in vivo. If confirmed, the hypothesis would resolve a long-standing mystery of why many animals (including humans) have two types of hair cells, in terms of their different responses to noise. [KW]

Noise also plays a critical role in **neocortical interactions**. Neocortical data obtained from experiments on rats [31] serve as the basis for a biologically relevant mesoscopic neural network model. Exact results can be obtained for noise driven binary interactions; the robustness of certain dynamical properties allow us to extrapolate to more complex types of interactions. This approach fills a gap between detailed biophysical simulations which cannot make rigorous global predictions and generalized models which allow exact statements but on a level of description remote from biology. [KW,SPD,WLD,PC]

Analysis of **bioinformatics** data, such as the sequences derived from the structure of proteins and DNA molecules, reveals that these data are "chaotic" in the sense that along a molecule the spatial variation is analogous to the temporal variation in chaotic systems. These experimental findings motivate application of methods of analysis of chaotic systems to this new domain, with overall aim of attaining new insights into the complex mechanisms governing genetic information transfer. One goal is to develop new computationally tractable models that combine observable and hidden variables, such as the Hidden Markov models, train and test these models on available data, and verify their predictions. [LAB]

Novel **nonlinear approaches to neuroscience** include neuromorphic engineering, hybrid neural oscillators, hybrid neural microsystems, and feedback control. SPD uses very large-scale integrated (VLSI) circuits to model biological systems. Already developed are the VLSI models of **motor-control systems** that produce rhythmic oscillations. Future work will develop systems that incorporate mechanical actuation in robots and sensory feedback. This feedback modulates the nonlinear behavior in a variety of ways, providing a unique window into detailed dynamical properties of movement control in biological systems. Many biological systems exhibit complex, **nonlinear oscillations**, difficult to study in living systems because of the lack of control and range of the underlying neural parameters. GT/EU group will develop the technology to create **hybrid neural oscillators** that integrate wetware and silicon, interfacing living matter with VLSI models of these elements, implemented either in VLSI circuits and/or real-time computation. The resulting hybrid systems merge biological realism with the controllability that is only present in the artificial systems, and facilitate in-depth study of the biophysics and dynamics of the biological circuits. [SPD,WLD]

The **dynamical behaviors of neuronal populations** are robust, adaptive, and rich in the set of their computational primitives. Harnessing the power of this tissue would facilitate the ability to develop engineered systems that emulate the complex computational power found in nervous systems. However, it is difficult to interface to these systems in an effective manner. GT/EU group will developed new techniques to interface to large populations of neurons in a dish, and use neural tissue to control the external world in a closed-loop configuration, in which the neurons adapt to their external environment. The use of nonlinear dynamics techniques combined with these advances in the hybrid technology will lead to use of neural tissue for a variety of tasks, from the **control** of machines to creation of **biological computers**. [SPD,WLD]

In a new EUSM/GT collaborative effort the experiments monitor **spatiotemporal activity in the human brain** while the subject performs simple motor or cognitive tasks. Activity is measured using continuous magnetic resonance imaging, resulting in time- and space-resolved images. Despite ample evidence for the nonlinearity of neural activity, conventional neuroimaging studies take a linear, subtractive approach to experimental design and analysis. In contrast, the EUSM/GT approach is grounded in notions of nonlinear dynamics, e.g. when a continuous variation of the cognitive task results in a sudden qualitative change in behavior, it is viewed as a bifurcation of the neural system. In addition to direct analysis of the spatiotemporal data by modern time series methods, model-based approaches are used to investigate how physiological factors such as slow hemodynamic response affect the dynamics [32, 33]. [GSB,KW]

C.4 Development of cross-cutting methodologies

It is the very essence of nonlinear science that the same researchers contribute to widely different fields, here split into different MRCs. Research advances in nonlinear science are inseparable from the training it offers, and that is the core effort that all PFCNS 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 PFCNS, 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 [34]). 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 PFCNS 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 MRCs 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 initatives, PFCNS will offer an advanced web based year-long gradute course [35]. 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 PFCNS training program will be supplemented by the following important components:

Welcoming workshop/retreat, before the start of each fall semester, will introduce the incoming young researchers to the PFCNS. 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.

Interdisciplinary Nonlinear Science Seminar series, initiated in January 2001, has drawn a wide attendance from the participating departments and institutions. PFCNS would enable us to run the seminar on an ongoing basis and to broaden its scope to engineering and biological applications.

Graduate Student Seminar 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.

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.

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 PFCNS faculty, and who demonstrate potential as external mentors to our graduate students and junior researchers.

Regional Nonlinear Science 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 the honor of late Joseph Ford, one of the pioneers of classical and quantum chaos and a former professor at GT, will sponsor several outstanding postdoctoral fellows each year. J. Ford 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.

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 PFCNS can make possible.

D Diversity and outreach

D.1 Internship program

PFCNS will offer to students and post-doctoral fellows of exceptional promise (either from PFCNS, or from outside) **internship** support, the goal of which is to significantly broaden and strengthen their education. For example, a trainee working on theoretical projects might intern in an experimental lab, 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.

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 form the basis for a publication. The interships will be reviewed after the first three months by the PFCNS 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.

D.2 Regional, national and international collaborations

The internships and other training initiatives will make use of the extensive connections the PFCNS faculty has with other institutions and labs. Close contacts between the advisors and interns' hosts will contribute substantially to turning such contacts into full-fledged collaborations.

Examples of such cross fertilization are already in place: KW interacts closely with F. Jaramillo at Carleton College in studies of the effects on noise on auditory hair cells. As a member of the External Advisory Board for Space Medicine and Life Sciences Research Center, GPN advises researchers at the Morehouse School of Medicine on fluid mechanics aspects of tissue growth. The PFCNS fluid dynamics Physics & ME program interacts with GT Institute of Paper Sciences & Technology where the fundamental problem of pattern formation is relevant to increased efficiency in coating of paper. As an extension of the work in the spatiotemporal dynamics of human brain activation, 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.

GT provides a rich intellectual environment which greatly enhances proposed PFCNS effectivness as a platform for cross-disciplinary interactions. The School of Mathematics CDSNS contributes excellent visiting researchers, seminars, and training opportunities in mathematical methods for nonlinear science. To name but a few, preeminent scientists such as E. Carlen, M. Loss, L. Erdos, E. Harrell, K. Mischaikow, W. Gangbo (Mathematics / CDSNS), M. Borodovsky (Biomathematics), D. Dusenbery, R. Wartel (Biology), G. Hentchel and F. Family (Physics, EU), F. Jaramillo (Biology, Carleton College), and N. Chernov and N. Simanyi (Mathematics, U. of Alabama in Birmingham) will interact with PFCNS faculty and visitors.

Nationally PFCNS will collaborate intensively with the NSF IGERT programs at Northwestern, Cornell and U. of Arizona, as well as with a number of other leading centers for nonlinear science. Internationally, some fifteen *"Sister Nonlinear Science Centers"* located in Mexico, Germany, Denmark, United Kingdom, Italy, Israel, Argentina, Hungary, Chile and Austria would collaborate with PFCNS in organizing workshops, exchanging researchers, and hosting interns. (For a complete list, please check the Center webpage [36].)

D.3 Educational outreach

Following up on the NSF Southeast Applied Analysis Center (GIG #9632032) successful outreach program, PFCNS members will be sent to deliver lectures on various topics of modern physics, biology and mathematics as **Center Ambassadors** to Southeast region nonresearch educational institutions and historically black colleges and universities. PFCNS 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**. The goals of the outreach program are to inspire bright undergraduates, K-12 students, and teachers, to build bridges to faculty isolated at nonresearch institutions, and to inform talented students about the attractiveness of GT graduate programs.

E Administration and assessment

The proposed PFCNS director is P. Cvitanović (GT physics). Prior to moving to GT, Cvitanović co-founded and directed (1993-1998) the Center for Chaos and Turbulence Studies at the Niels Bohr Institute, Copenhagen, one of Europe's leading centers for nonlinear science. In the period 1997-2000 Cvitanović led the initiative to create a Center for Complex Systems at the Northwestern University, and was the PI on the NSF IGERT Complex Systems in Science and Engineering program, awarded to Northwestern in 2000. He is currently the Glen Robinson Chair in Nonlinear Sciences and director of the newly created CNS.

Due to the full cross-disciplinary integration of the four MRCs, the day-to-day training, research, and other activities of the program will be supervised by the Executive Committee (see sect. 4), which will ensure that fellowships, internships, visitor invitations, and other PFCNS resources are awarded in accordance to the goals of the program. Faculty status implies no entitlement to any part of PFCNS resources; Executive Committee will base its decisions solely by quality and cross-cutting impact of each project considered.

The evaluation of the program 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 PFCNS J. Ford Fellows, student internships, MRCs 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 MRCs research impact, recruitment, retention, PhD theses time-to-degree measures, publications, and a visit of an external expert committee.

4 PFCNS Faculty

Director:

P. Cvitanović, Glen Robinson Chair, Professor, Physics (COS)

Executive Committee:

L. A. Bunimovich, Regents' Professor, Mathematics (COS)
K. Wiesenfeld, Professor, Physics (COS)
M. Schatz, Assistant Professor, Physics (COS)
S. P. DeWeerth, Associate Professor, Electrical and Computer Eng. (COE)

Faculty:

G. S. Berns, Assistant Professor, Psychiatry (EUSM)
W. L. Ditto, Professor, Biomedical Engineering Department (GT/EU)
R. F. Fox, Regents' Professor, Chair of School of Physics (COS)
J. Geronimo, Professor, Mathematics (COS)
R. W. Ghrist, Assistant Professor, Mathematics (COS)
R. Grigoriev, Assistant Professor, Physics (COS)
R. Hernandez, Director CCMST, Assistant Professor, Chemistry (COS)
G. P. Neitzel, Professor, Mechanical Engineering (COE)
A. Shilnikov, Assistant Professor, Mathematics, Georgia State University
T. Uzer, Professor, Physics (COS)
E. R. Weeks, Assistant Professor, Physics (EU)

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

GT	Georgia Institute of Technology
EU	Emory University
EUSM	Emory University School of Medicine
GSU	Georgia State University
COS	College of Sciences
COE	College of Engineering
BME	Georgia Tech/Emory Biomedical Engineering Department
ECE	Department of Electrical & Computer Engineering
ME	Mechanical Engineering
Chem	School of Chemistry and Biochemistry
Math	School of Mathematics
Phys	School of Physics
CCMST	Center for Computational Molecular Science & Technology
CDSNS	Center for Dynamical Systems & Nonlinear Studies

5 Institutional Resource Commitments

Georgia Tech boasts a strong faculty in nonlinear sciences, ranked 5th nationally in the 1999 U.S. News and World Report survey. Its commitment to strengthening the research effort in this field is demonstrated by recent chaired faculty appointment in physics (Cvitanović), continued recruiting efforts in mathematics (through the CDSNS) and physics (junior experimental nonlinear physics faculty search in 2001, senior experimental nonlinear physics faculty search for 2002), and planned expansion in biosciences (including chair appointments).

Georgia Tech actively encourages cross-departmental and cross-disciplinary research. The *GT Center for Nonlinear Science* (CNS) which began operation July 2001 aims at furthering such an environment and acts as a seed program for the proposed PFCNS which will make it possible to span GT COS, GT COE, EU Medical School and Georgia State University nonlinear science efforts in one center.

The PFCNS office and the common meeting room will be housed in Physics. The building already has student computer laboratories, and another experimental computation laboratory is under construction in the Math building. Except for the laboratories in the EU Medical School, the participating faculty laboratories are situated at GT. An effort will be made to provide shared office space and computer facilities for the PFCNS junior researchers and graduate students.

The PFCNS will require substantial single- and parallel processor computing resources to implement the MRC's objectives. GT's CCMST, whose codirector, R. Hernandez, is CNS member, already provides a 72-processor IBM SP2. Up to one third of this resource will be available to the PFCNS with the part-time funding of a research scientist and a commitment to PFCNS to upgrade part of the facility at year 3.

The Deans of the participating Colleges and the Institute, at the level of the University's Vice-Provost for Research, strongly support the initiative, and are already funding the CNS for an initial three-year period. As a seed cost-sharing contribution, GT has committed $147K/year funding for period 2001-2004, providing funding for 2-3 postdoctoral research associates, a distinguished lecturer series, visitors, workshops, the Nonlinear Science seminars, full-time secretarial support, and part-time computer/web support. In addition, GT has already committed $30k for equipment funds to cover the equipping of research associates' offices, research infrastructure including computer network, servers, a platform for intensive computation, software, printers, and CNS office equipment.

6 Summary Table of Requested NSF Support

Activity	Year One	5 Year Total
MRC 1: Chaos	\$279,455	\$1,397,277
MRC 2: Extended Systems	\$279,939	\$1,399,695
MRC 3: Dynamics and Biology	\$279,939	\$1,399,695
MRC 4: Cross-cutting Methods	\$561,375	\$2,806,875
Shared Facilities	\$321,652	\$1,338,256
Seed Funding and Emerging Areas		
Education and Human Resources	\$98,600	\$493,000
Outreach	\$56,250	\$281,250
Administration	\$71,152	\$355,762
Total	\$1,948,362	\$9,471,810

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