3 Project Description

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B List of Faculty Participants

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

WCAS	Weinberg College of Arts and Sciences
MEAS	McCormick School of Engineering and Applied Science
NUMS	Northwestern University Medical School
BME	Department of Biomedical Engineering
ChE	Department of Chemical Engineering
ECE	Department of Electrical & Computer Engineering
ESAM	Department of Engineering Sciences & Applied Mathematics
MSE	Department of Materials Science and Engineering
Math	Department of Mathematics
ME	Department of Mechanical Engineering
NBP	Department of Neurobiology & Physiology
PaA	Department of Physics & Astronomy
Phys	Department of Physiology

C Thematic Basis for the Group Effort

Over the past two decades, investigations of nonlinear systems have revealed that the simplest laws of nature can lead to bewilderingly complex dynamics, and yet that such dynamics exhibit universal features which are largely independent of the details of the underlying system. Thus, phenomena as disparate as neuronal dynamics and mixing of granular materials can be studied with the same mathematical tools. Common themes that arise in the study of nonlinear systems include their qualitative dynamics, structural stability, long-term behavior, chaos, bifurcations, and the impact of symmetries on the dynamics.

By stressing the unity of the underlying concepts and using the accumulated experience of scientists from diverse backgrounds, investigators of nonlinear phenomena are transforming important problems once considered intractable, or even ill-posed, into promising new fields. Methods developed in the study of nonlinear systems are now being applied at Northwestern University to such areas as pattern formation, quantum theory, biomotor control, computational neuroscience, nonlinear optics, crystal growth, granular flows, biological fluids, mixing, nonequilibrium transport, and combustion. These problems cut across many fields, and traditionally have been studied only by researchers in their respective fields, e.g., chemical, mechanical, or electrical engineering, physics, applied and pure mathematics, or the biological and health sciences.

The aim of the proposed program is to provide unique training through 14 fellowships that will allow graduate students at Northwestern to work on problems involving nonlinear phenomena, without being limited to the nonlinear problems specific to a given subfield. Typically, Ph.D. students follow a departmental core curriculum and then specialize in a single focused area of research. Scientific experience of a broader and more cross-disciplinary nature comes later, if at all, and then within the context of needing to solve a specific problem within a short time span. This is not conducive to the type of broad, systematic study needed to give a researcher the background necessary to move easily between subfields, and to apply techniques learned in one subfield to the problems of another.

We feel that a systematic study of nonlinear systems should be an important part of the education of all Ph.D. students who will be dealing with complex systems later in their careers. Unquestionably, the most remarkable single aspect of nonlinear systems is the commonality of the mathematics that describe them, despite the wildly varying contexts. It is clear that a strongly cross-disciplinary program of study for nonlinear systems will be far superior to any based in a single department or discipline.

The proposed IGERT program will produce PhDs considerably different from those with a traditional science or engineering education and training. Fellows will be broadly trained in all aspects of nonlinear phenomena and thus better prepared for the rapidly changing needs of industry and academia. The program will have four primary components:

1) Fellows will take part in a year-long group research project – similar in spirit to the task forces often assembled in research environments to brain-storm on innovative ways to attack new problems – in which four or five graduate students from a spectrum of technical backgrounds will investigate a topic (distinct from their Ph.D. thesis research) under the

joint supervision of at least two faculty from different disciplines. The project will culminate in a written report and oral presentation to the students and faculty participating in the IGERT program. The educational aims of the project are to give the students in-depth research experience in areas besides that of their Ph.D. theses, to prepare them to work as part of a cross-disciplinary team akin to those they will work with later in their career, and to develop the communication skills necessary to discuss their results with an educated audience unfamiliar with the topic.

2) Fellows will be expected to take an internship for 3 - 6 months at an industrial or government lab, or at another University. For example, a theoretician working on neuro-transmission or nonequilibrium crystal growth might elect to spend his or her internship in a laboratory to observe or run an experiment directly related to the theory.

3) Fellows will actively participate in the yearly workshops, the weekly seminars and the visitor program organized by Northwestern's Nonlinear Science Program. These workshops and seminars are highly cross-disciplinary in nature, as the faculty comprising the Nonlinear Science Program come from ten different departments and three schools.

4) The thesis research of the Fellows will be guided by a pair of faculty members with shared interests, but different research specialties and complementary expertise. This will further the cross-disciplinary training and help ensure that the Ph.D. dissertation has a broad impact.

The proposed IGERT program places great emphasis on students interacting with the broadest possible spectrum of experts. In addition to the internships, program participation of first-rate researchers from outside Northwestern is ensured through the institutional funding of a yearly workshop, a visitor program and a weekly seminar. A special effort will be placed on recruiting and retaining minority and women students within the program, through mentoring programs, special seminars, enhanced fellowships, and a summer research program for undergraduates.

As detailed elsewhere in this proposal, Northwestern University has excellent existing faculty and research infrastructure in nonlinear science, and the right mix of specialties, to offer cross-disciplinary Ph.D. training. The Nonlinear Science Program faculty already works on a number of interdisciplinary research projects. Inevitably, the thesis topics studied at the onset of the IGERT program will reflect the current interests of the individual faculty members. However, a major benefit of the IGERT grant will be to act as a vehicle for the generation of new interactions, and hence the development of nonlinear-science projects in new areas.

The proposed IGERT program will be instrumental in fusing the faculty from different departments at Northwestern into a Nonlinear Science Institute, which will in turn strongly facilitate Ph.D. training by allowing the group to recruit, train, and financially support graduate students for the express purpose of completing a cross-disciplinary Ph.D. in nonlinear systems. In the long run, IGERT will seed a basic institutional change, with faculty from diverse specialties sharing students and building collaborations that far outlast the IGERT program itself.

D Major Research Efforts

Northwestern University scientists pursue a comprehensive range of research within the unifying theme of nonlinear dynamics. We highlight here some of these research efforts:

The richness of **pattern formation** phenomena has stimulated very active research on **spatially extended dynamical systems**. Classic examples occur in fluid convection driven by temperature gradients, water waves excited in liquid layers, combustion–flame fronts in gases and solids, and coarsening in elastically stressed solids. Pattern formation issues arise in the study of Turing patterns in chemical and biological systems, in the analysis of **information processing**, storage, and retrieval in the brain, and in the characterization of **convective transport** in poroelastic, stressed media such as lung tissue. Applications to materials science arise in modeling the dynamics of **thin films**, **interfaces**, and **dendritic growth**.

Powerful theoretical tools developed for the characterization of localized structures and **spatio-temporal chaos** are complemented by a theoretical description of maps and flows, of relevance to experiments on the mixing of highly viscous fluids as well as transport in **granular materials** and **complex fluids**. Recently discovered **oscillons**, localized waves in vibrated granular media, are conceptually related to **solitons**, whose importance as long-distance information carriers has been exploited in applications of **nonlinear optics** to telecommunications and optical processing.

Mathematical and mathematical physics research in nonlinear dynamics at Northwestern University focuses on **ergodic theory** as well as **classical and quantum chaos**; it includes work on knots that occur as closed orbits of flows and periodic orbits of low dimensional dynamical systems, as well as geometrical and dynamical aspects of geodesics on general manifolds. The **periodic orbit theory** applies these mathematical results to physical problems such as far-from-equilibrium transport, conductance of mesoscopic devices, and the semiclassical quantization of classically chaotic systems.

Applications to **computational neuroscience** range from research on synchronized oscillations and chaos in recurrent neural networks to the design of computationally efficient nonlinear controllers for limb motion.

We now describe these research efforts in more detail, with special emphasis on connections that would gain strength and coherence under the IGERT program. Throughout the text, the contributing researchers are indicated by initials; (SHD) stands for (S.H. Davis), and so on.

D.1 Pattern Formation

Background

Spatiotemporal patterns appear spontaneously in a wide range of physical, chemical, and biological systems when they are driven sufficiently far from thermodynamic equilibrium. The classic example is Rayleigh-Bénard convection in a fluid layer heated from below. For sufficiently strong heating fluid motion sets in, typically in the form of convection rolls.

As the driving parameter is increased, regular patterns are supplanted by patterns that are more and more irregular in space and time, resulting in states that are intermediate between ordered patterns and turbulence. Some snapshots of patterns from two different fluid experiments are presented in Fig. 1; more examples, including movies, can be found at `www.phys.nwu.edu/~canis/`.

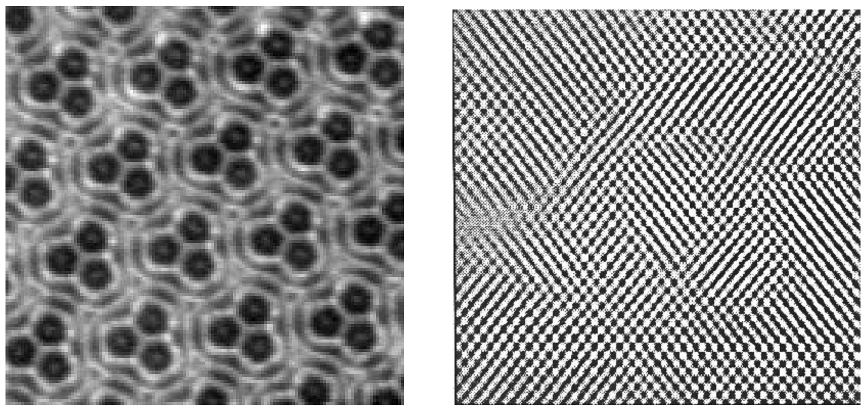

Figure 1: a) Super-lattice structure in parametrically excited surface waves [1]. b) Oblique waves ('zigs' and 'zags') and traveling rectangle patterns observed experimentally in electroconvection of nematic liquid crystals [2].

Early pattern-formation research focused on relatively simple spatially periodic structures, *e.g.* convection rolls or hexagonal structures. The open questions addressed by current research concern structures with more complexity. These can be spatially periodic complex patterns (see Fig. 1a), spatially localized structures, or structures that are chaotic in time as well as space ('spatio-temporal chaos'). Applied pattern formation research is motivated by the goal of utilizing the spatial structures, or, in the event that they are undesirable, of suppressing their formation. In either case the origin and nature of spatial structures must be well understood. Fundamental theoretical challenges arise because pattern-forming systems represent nonlinear dynamical systems with many degrees of freedom. A vivid illustration can be found in electroconvection of nematic liquid crystals (Fig. 1b) where patterns consist of ever-changing patches of traveling convection rolls of different orientation. Research challenges include giving precise characterizations of such states, identifying the relevant mechanisms for their creation, and being able to control their evolution.

Potential for cross-disciplinary graduate training

Pattern formation is not limited to fluid systems. In materials science the spatial structures arising at the liquid-solid interface of a growing crystal are known to greatly affect the properties of the resulting crystal, and therefore have a profound technological impact (SHD,PV). Similar structures are observed in flame fronts where they affect the combustion process (BJM). Both topics are discussed in section D.6. In laser beams with large cross-sections, transverse spatial structures in the form of waves can develop. They are undesirable in many applications and have led to active and promising research in pattern control. For other examples of pattern formation in nonlinear optics, see section D.4.

Fundamental to pattern formation research is the observation that the patterns are determined by cooperative interactions on large scales and hence many aspects of the phenomena can be understood on a "macroscopic level". Only certain aspects of the detailed microscopic physics of the fluid or laser, say, contribute to the overall behavior, allowing a unified approach to phenomena in diverse physical, chemical, and biological systems. This approach, which accentuates certain key concepts, applies when an underlying symmetric state loses stability with the change of a parameter. Nonlinearity is essential for the saturation of the instability. Moreover, symmetries of the system typically result in the simultaneous presence of many destabilizing modes; for a linear system, the resulting state would be an arbitrary superposition of these exponentially-growing modes. In pattern-forming systems nonlinearity leads not only to saturation of instabilities, but also to selection of certain modes which then dominate the system (so-called "pattern selection").

Central features that enter the unified description of patterns include the symmetries of the problem and the character of the instability. Remarkably, this information is often sufficient to make qualitative and semi-quantitative predictions for the patterns that arise. For example, it was possible for HR and collaborators to predict the outcome of a periodic forcing of the traveling waves observed in electroconvection [3] well before the microscopic equations describing the traveling waves were known [4].

Examples of ongoing research

HR investigates **spatio-temporal chaos** in various types of systems. Work with his student Granzow reveals a transition between an ordered, stripe-like state of spatio-temporal chaos to a disordered one involving the unbinding of defects/vortices. It raises questions regarding connections to phase transitions in equilibrium. Does the chaotic dynamics play a role similar to thermal noise in equilibrium? What are the differences? These studies are therefore closely connected to the theory of phase transitions (SAS). In electroconvection (cf. Fig. 1b) spatio-temporal chaos occurs immediately above threshold [2] and is therefore one of the few cases that hold promise for *quantitative* analysis within Ginzburg-Landau equations (HR). PC analyzes spatio-temporally chaotic dynamics using the unstable periodic orbits embedded in the chaotic attractor; this research is discussed in section D.3.

Parametrically excited patterns arise, for example, when a fluid (or granular medium) is subjected to a periodic vibration. This pattern formation mechanism is one focus of the theoretical research of MS and her graduate students, and the experimental program of PBU and his students. For example, "superlattice patterns" observed only recently in experiments on parametrically excited surface waves (Fig. 1a) were predicted to exist on the basis of symmetry and bifurcation theory arguments by MS and her collaborators [5]. The 1998 Ph.D. thesis of S.L. Judd investigated superlattice Turing patterns in chemical reaction-diffusion systems [6]. MS and her graduate student J.J. Derwent are currently investigating partial synchronization, pattern formation and chaos in spatially discrete arrays of Josephson junctions. In this system, parametric instability is responsible for a lack of total synchronization of the array. Their investigation focuses on the effect of spatio-temporal pattern formation on the current-voltage characteristics of this high-frequency electronic device [7].

For fluid surface waves, PBU has developed a sophisticated vibration control method and is perfecting a novel visualization technique which will enable a more quantitative comparison of experiment and theory in this area.

In recent experiments various **localized structures** confined to only a small part of the homogeneous system have been observed. PBU has found localized circular excitations of the surface ('oscillons') in vibrated granular media that can form a variety of bound states like 'dipoles', 'trimers', and chains [8]. What keeps these structures from spreading over the whole system? With graduate student Catherine Crawford, HR investigates localization mechanisms theoretically. This provides feed-back for PBU's experiments and identifies connections to localized structures in electroconvection ('worms') [9] as well as in optics (section D.4) and combustion (section D.6).

Proposed new cross-disciplinary research

Pattern formation has great potential for cross-disciplinary investigations arising, e.g., in interfaces (section D.6), nonlinear optics (section D.4), as well as in granular media [10] (section D.2). Here we sketch additional examples that connect pattern formation research in various participating departments. These collaborations will be greatly facilitated by the IGERT grant.

Together with a beginning applied mathematics graduate student Kimberly Montgomery, MS has initiated a research project on controlling pattern formation in a model of a coherently pumped three-level laser. Here the goal is to design a feedback control scheme, based on the symmetries of a targeted space and time periodic patterned state, that will lead to a stable regular pattern in place of the spatio-temporally chaotic state that occurs in the absence of the control. This project will benefit from collaboration with the IGERT nonlinear optics group (section D.4), as well as ideas developed by PC and collaborators on identifying unstable periodic orbits in dynamical systems (section D.3).

Together with graduate students, MS investigates the dynamics of coupled discrete nonlinear elements such as Josephson junctions or lasers. Building on the insight on synchronization gained in these studies, we propose to address, in collaboration with SAS (Physiology), the binding problem in neural networks. If a neural network is presented with a number of objects with a number of different properties (e.g. a brown, low chair and a yellow, tall lamp) then all the items and properties (brown, low, yellow, tall, chair, lamp) are excited in the network but it is not clear how the binding of "brown" and "low" with "chair" is performed in the brain. Conjectures based on binding through coherent oscillations in neural activity have received recent experimental support; questions on the conditions under which such synchronous firing can arise and be sustained do now require analytic and numerical investigation.

Another new direction of research will address the extent to which neural networks, which are formulated using discrete elements, can be modeled by continuous fields (SAS,HR). This would open additional routes for analytical studies that might help address, for instance, the question of convergence of the Kohonen-algorithm for unsupervised learning.

D.2 Mixing

Background

Mixing of viscous fluids is important in the context of materials processing, reactive and non-reactive polymer processing, food processing, and stabilization of hazardous wastes. Transitional mixing is of relevance in bioreactors, and turbulent reactive mixing is critical in the understanding of atmospheric chemistry and pollution control. Liquid-solid mixing plays a critical role in pharmaceutical manufacturing and the paper and rubber industries. Solid-solid mixing is important in catalyst preparation, blending and processing of ceramics precursors, and the pharmaceutical industry. In all of its guises, opportunities for advances in mixing research are enormous and the potential to impact engineering practices quite significant. Fundamental developments in mixing research for fluid and granular solids applications have over the past decade largely been spurred by developments in the theory of nonlinear dynamics [11, 12].

Potential for cross-disciplinary graduate training

Mixing is an ideal test-bed for dynamical systems concepts and an excellent area for cross-disciplinary investigations.
(1) Experiments serve as a powerful aid to understanding; the interplay of physical and mathematical concepts - stretching and folding, periodic points, attractors, etc. - becomes vividly apparent in well-designed laboratory experiments.
(2) Mixing experiments serve as a training ground; it is relatively easy to design experiments to attract theory students to experimental projects for one or two quarters.
(3) The challenging open questions of mixing and segregation are best attacked by a confluence of viewpoints (mathematicians, physicists, chemical and mechanical engineers).

Ongoing Research

Three-dimensional mixing in stirred tanks is an area where concepts based on nonlinear dynamics can have a profound impact. Current engineering approaches focus on computational fluid mechanics. Work along this lines is currently underway in Dow Chemical (A. Harvey), Chemineer (A. Bakker), Eindhoven University of Technology (H.E.H. Meijer et al.), Rutgers (Muzzio et al.), and many other places. There is, however, a body of unexploited theory [13] and a need for carefully controlled experiments. Rather than trying to simulate the flow in a particular industrial mixer, J.M. Ottino (ChE) and collaborators are conducting controlled experiments and high precision computations in a 'fundamental mixing tank'. A short description of their results appears in [14]. The experimental work involves slicing a section of the tank by means of a laser sheet in order to determine experimentally a Poincaré section. The velocity field is measured by laser Doppler velocimetry, using the facilities of R. Lueptow in ME. Current collaborations involve a mathematician (I. Mezić, UC Santa Barbara) and further collaborations with Northwestern mathematicians are anticipated. JMO has trained a ChE postdoc, a ChE student, and a ME student in custom-written simulations, commercial CFD codes and fluids experimentation. This collaboration takes concerted effort which will be facilitated through a formal IGERT program.

In a cross-disciplinary collaboration between ChE and the Medical School, chaotic **mix-**

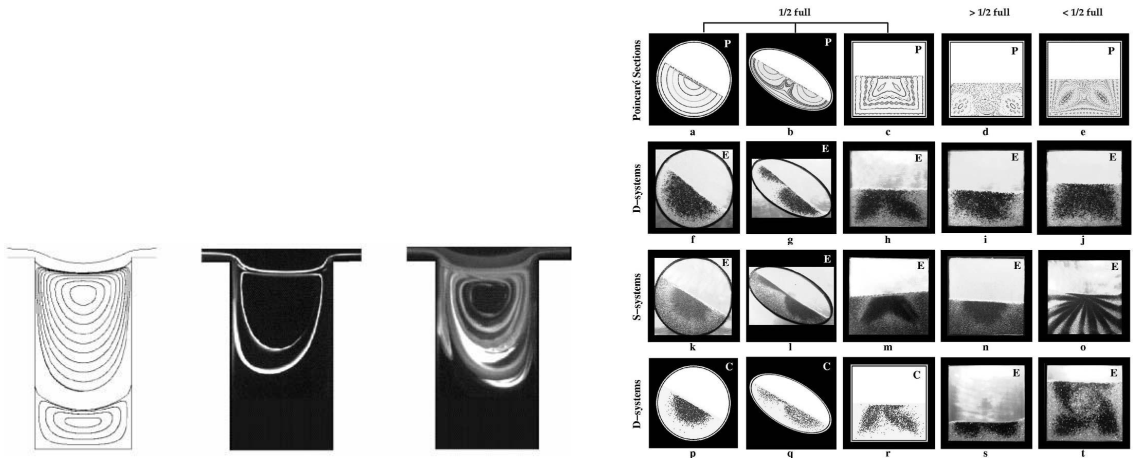

Figure 2: (a) Steady 2d streamlines in cross section of groove, produced by boundary integral equation method simulation. No mixing occurs between fluid in the groove and the stream outside. (b) and (c) tracer-advection experiment after 1 and 30 periodic oscillations of the free stream flow. Dye stream along top of groove is now entrained into grooved cavity. (d) Competition between mixing and segregation in granular material in circular, elliptic, and square tumblers.

ing and transport in bioreactors has been investigated [15]. The motivation for this study is that patients undergoing bone marrow transplantation after high-dose chemotherapy experience reduced or eliminated platelet and neutrophil counts, and consequently suffer from bleeding and infection traumas. *Ex vivo* production of hematopoietic cells can reduce patient risk by supplying the necessary cells until transplanted. The ultimate goal of the research is to characterize and modify the flow around hematopoietic cells so as to provide adequate nutrient and chemical balances without damaging or unintentionally harvesting the cells. Chaotic advection is ideal for this purpose. The geometry initially studied consists of a series of parallel grooves, perfused by fluid flowing transverse to the grooves. The simplest steady flow in this geometry produces closed, 2D streamlines (see Fig. 2) with only diffusive transport between the fluid in the groove where the hematopoietic cells would reside and the free stream above. To produce chaotic transport, the free stream flow is periodically modulated. Fig. 2 shows experimental quasi-2D mixing of a dye into such a groove after 1 and 30 oscillations respectively. This project can be of interest to students in biomedical engineering, physics, and applied mathematics.

A set of problems complementary to fluid mixing arises in **chaotic granular advection** [12]. Remarkably, despite the considerable differences between fluids and grains (grains can arch, segregate, avalanche, and must dilate in order to flow), one can apply some of the same nonlinear dynamics tools to granular systems. For example, consider a thin, quasi-2D tumbler consisting of two parallel plates separated by a small distance. If the plates enclose a half-filled cylinder of grains, mixing in the tumbling regime is fairly slow and mainly diffusive. If, however, the plates enclose a square container, again half filled, then the flow is periodic. Consequently, chaotic advection is produced [17], very much as periodically driving 2D fluid systems can produce chaotic advection.

In many applications it is desirable to control **high Reynolds number mixing in fluids** between the bulk flow and the boundary layer region adjacent to a wall. For example: heat transfer near a wall relies on rapidly exchanging boundary layer fluid with the ambient flow; NOx emissions in an internal combustion engine can be reduced if the fluid in the incompletely combusted boundary layer is swept into the interior of the cylinder; mixing of momentum between the boundary layer and the outer flow can reduce vehicle drag and noise. In many mixing scenarios, vortices are the main agents of mixing between the bulk and boundary layer. In SL's collaborative research involving ME and ESAM, a model has been developed for a vortex interacting with a boundary layer at high Reynolds number [19]. The results reveal that though mixing is accomplished through several mechanisms, the contribution of each mechanism to mixing depends on only two parameters: the strength of vortices relative to the boundary-layer vorticity, Γ, and the height of vortices relative to the thickness of the boundary layer, d. Through this effort the optimal performance in terms of (Γ, d) can be mapped out and the optimization schemes can be compared with measurement.

Proposed new cross-disciplinary research

This research is ideally suited for student participation; the students involved in these projects develop molecular dynamics simulations, continuum simulations in the presence of diffusion, they study chaotic advection, and the experiments required are comparatively simple, yet reveal distinctly non-trivial dynamics.

Competition Between Chaos and Segregation. Mixing of granular materials provides fascinating examples of pattern formation and self-organization and some of the simplest examples of the interplay between chaos and self-organization that can be studied in the laboratory. Nevertheless, the understanding of the fundamentals of granular segregation and mixing remains incomplete. Often, granular systems evolve quickly through complex dynamics into a state of self-organization. For example, in a short tumbled cylinder this may lead to radial segregation [16]; and in long cylinders to axial banding. More mixing action does not guarantee a better-mixed final system; in fact, the very same forcing used to mix may unmix. Thus, self-organization results from two competing effects: chaotic advection or chaotic mixing, as in the case of fluids, and flow-induced segregation, a phenomenon without parallel in fluids. An example is shown in Fig. 2d, where the pattern arises from the suppression of mixing by the segregation. The rich array of behaviors is ideally suited for nonlinear dynamics based investigations, with the experiments interfacing directly with the theory. A brief summary of possibilities is due to appear in [18].

Future research under the auspices of the IGERT grant is planned to develop a measure of mixing. This work will be connected with the research in JMO's group (ChE) and Cvitanović's group (PaA) on mixing and chaos (see section D.3).

D.3 Ergodic Theory, Classical and Quantum Chaos

Background

Nature is rich in systems governed by simple deterministic laws whose asymptotic dynamics is highly complex, systems which are locally unstable but globally recurrent. How do we describe their long term dynamics? This is the question addressed by the ergodic theory in mathematics, and the theory of chaotic dynamics in physics.

Recent advances in the theory of dynamical systems have brought a new life to Boltzmann's mechanical formulation of statistical mechanics, especially for systems far from equilibrium. A century ago it seemed reasonable to assume that statistical mechanics applies only to systems with very many degrees of freedom. More recent is the realization that much of statistical mechanics follows from chaotic dynamics, and already at the level of a few particles the dynamics is irreversible. In the Sinai, Ruelle and Bowen (SRB) generalization of Boltzmann's notion of ergodicity to dissipative systems in nonequilibrium stationary states the attractor plays the role of a constant energy surface, and the SRB measure is a generalization of the Liouville measure. In beauty and in depth the modern ergodic theory ranks along with thermodynamics, partition functions and path integrals amongst the crown jewels of mathematical physics.

The Bohr-Sommerfeld theory of the 1920's, while very successful for hydrogen, was a disaster for helium. The failure was no fault of the old quantum mechanics, but due to subtleties of classical mechanics. Classical helium is a 3-body problem, and the 1913-24 theory could not quantize nonintegrable systems. Today we know that the unstable periodic orbits form the skeleton for chaotic dynamics, and that a quantum Bohr-Sommerfeld amplitude can be associated with each such orbit. One of the recent developments is the discovery that the zeros of Ruelle zeta functions of classical ergodic theory also yield excellent estimates of quantum resonances. The modern theory solves the problem that Bohr himself would have loved to see done back in 1916: a "planetary" calculation of the helium spectrum.

Today the **theory of dynamical systems** is a vigorous mathematics discipline, interacting with fields as diverse as number theory, geometry and especially physics. Mathematical studies of physical systems provide paradigms for the study of nonlinear systems. Mathematical theory of dynamical systems is in turn enriched by ideas from physics, notably thermodynamics.

Potential for cross-disciplinary graduate training

Research in ergodic/chaotic systems is an interdisciplinary field *par excellence*, with contributions ranging from rigorous mathematics to theoretical physics to physical chemistry and neurophysiology, merging seamlessly into a methodology that any graduate student in the groups participating in the Nonlinear Science Program needs to master today.

For example, courses based on P. Cvitanović's graduate textbook on Classical and Quantum Chaos [29] are attracting a broad graduate audience, and the physics thesis of PC's student H.H. Rugh on the analyticity of the Fredholm determinants has been well received in the mathematics community. The converse is true for much of the mathematical work in dynamical systems. Hamiltonian systems in particular are a rich source of dynamics important in many fields of research pursued by the Nonlinear Science Program faculty. The n-body problem of Newtonian celestial mechanics, geodesic flow on Riemannian manifolds, forced nonlinear oscillators and other conservative systems in physics and engineering, both on the classical and quantum levels, are all Hamiltonian systems.

In the quantum arena, physics research on the perturbative corrections to semi-classical trace formulas, and inclusion of the tunneling and diffraction effects, relies heavily on the asymptotic techniques developed by applied mathematicians, and in turn inspires pure mathematics research in problems such as the Riemann hypothesis.

One of the most beneficial roles of the proposed IGERT funding would be to enable the graduate students in math, physics and applied math to follow a broader and more flexible course of study, and facilitate bringing to Northwestern University visitors which would strengthen graduate training in both theoretical physics and mathematics, but which currently do not fit well in any of the departmental seminar and lecture series.

Examples of ongoing research

Studies in **dynamics** at Northwestern focus on the periodic orbits of low dimensional systems (J. Franks, PC), geometric and dynamical problems connected with geodesics on general manifolds (K. Burns, A. Wilkinson), and the stability of ergodic properties of smooth systems (KB, AW).

In two-dimensional systems, there is a strong connection between a rotation vector and the existence of periodic points. Initially formulated for the annulus, the theory has been extended by JF and his Ph.D. students [21] to surfaces without boundary of various genus, where the existence of certain types of periodic points may imply the existence of infinitely many. Effective applications of the periodic orbit theory require detailed understanding of the **topological structure** of 2- and higher dimensional strange attractors of the Hénon type, an active research area of equal importance to mathematicians (JF,KB) and physicists (PC). To this end, PC works on generalizing the kneading theory for 1-d maps to 2-d, making it possible to construct the symbolic dynamics for many other systems of physical interest, in particular a variety of billiards and 2-d potentials.

Since the work of Anosov in the 1960's, it has been known that the **geodesic flow on manifolds** with negative curvature is ergodic. More recently it has been shown that certain manifolds with some areas of positive curvature but mainly negative curvature also have ergodic geodesic flows. KB has contributed to these developments [20], establishing, in particular, that it is possible to find metrics on spheres of all dimension which are ergodic. AW has also studied the geometric properties of geodesic flows, including the regularity of horocyclic foliations for nonpositively curved manifolds, a crucial aspect of Anosov's original proof of ergodicity [22].

The **periodic orbit theory** (PC) 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 such as helium. PC and collaborators have established that strongly chaotic systems can be described surprisingly accurately by means of **unstable periodic orbits**. So far the periodic orbit theory has been developed for classical and quantum non-integrable systems, and for renormalization group flows [29]. In particular, the cycle expansions [28] have contributed to the recent progress in the **semi-classical theory of chaotic systems** by improving the convergence of periodic orbit expansions and setting the stage for accurate tests of tunneling and other corrections to semi-classical approximations. The most exciting application of the theory has been to **quantum chaos** [27], where one can now experimentally measure the energy levels that the chaos theory predicts from the classical unstable orbits.

PC and students' analysis of **transport properties** of chaotic systems yields exact cycle expansion formulas for transport coefficients [29] without any probabilistic assumptions (such as the *stosszhalansatz* of Boltzmann). These results have physical applications to problems such as beam defocusing in particle accelerators or chaotic behavior of passive tracers in two dimensional rotating flows, problems which can be described as deterministic diffusion in periodic arrays.

The systems analyzed in the periodic orbit theory exhibit **hyperbolicity:** namely, uniform contraction and/or expansion in all, or almost all, areas of phase space. For these systems, periodic orbit behavior is predictive of the whole dynamics. Recent work of AW and KB has extended aspects of hyperbolic theory to systems that are only **partially hyperbolic**: in all regions of phase space, one finds behavior that is neither expanding nor contracting, together with some expansion/contraction. In particular, KB and AW have been able to show that many partially hyperbolic systems are **stably ergodic:** they and their sufficiently small perturbations are ergodic [23, 25, 26]. This leads to a modified version of Boltzmann's ergodic hypothesis of 1887: generically, stably ergodic systems are partially hyperbolic.

Furthermore, AW has recently exhibited that the periodic orbit theory in its current form breaks down for partially hyperbolic systems [24]. There exist, in dimension 3, stably ergodic, partially hyperbolic, systems whose Lyapunov exponents are all nonzero, but whose periodic points have all possible hyperbolic indices. The discovery of these systems was aided by the computer simulations of PC's student N. Søndergaard.

Proposed new cross-disciplinary research

PC plans to apply the periodic orbits theory of spatio-temporal "turbulence" of infinite dimensional dynamical systems to extended systems such as Kuramoto-Sivashinsky [30] and others studied intensively at Northwestern University by M. Silber, B.J. Matkowsky and H. Riecke (see section D.1). The theory should also apply to far-from-equilibrium processes in settings such as transport in granular media, investigated experimentally by groups of P.B. Umbanhowar (section E.1) and J.M.Ottino (section D.2), and in nanostructures studied in the lab of V. Chandrasekhar (PaA).

Implementation of the periodic orbit calculations requires firm understanding of the symbolic dynamics, and this is an area where the mathematical expertise (AW,JF,KB) is invaluable to physical applications (PC). The attainable accuracy in physical dynamical systems is always limited by external noise. PC plans to use external noise as a parameter which defines the smallest phase-space partitions that need to be taken into account in a given computation, and generate a finite approximation to the dynamics. In this ways methods of field theory, such as path integrals, will be applied to dynamical systems problems of mathematics. The theory of *wave chaos* has potential to be a general tool for engineering applications such as testing shapes of elastic objects by acoustic spectroscopy.

AW proposes to extend the study of partially hyperbolic systems to dimensions 3 and above, and to establish whether the recently discovered periodic point and Lyapunov exponent behaviors appear in higher dimensions; this work would be aided greatly by computer simulations carried out in collaboration with PC's group.

D.4 Nonlinear Optics

Background

As the transmission rate of optical communication systems has steadily increased in response to the growing demand for signal capacity, optical pulses have grown shorter in duration and increased in amplitude to the point where neither dispersion (the tendency for different frequencies of light to propagate at different speeds) nor the intrinsic nonlinear dependence of the index of refraction upon signal intensity can be neglected. In such a situation the basic model for the evolution of optical pulses is the nonlinear Schrödinger equation [31].

From a practical standpoint, the nonlinear dependence greatly increases the difficulty of understanding system behavior, in that standard linear communications theory is no longer applicable. On the other hand, new techniques have become available, since the nonlinear Schrödinger (NLS) equation possesses a rich mathematical structure. In particular, it is completely integrable via the inverse scattering transform [32], and can be thought of as an infinite dimensional Hamiltonian system. Perturbed NLS equations are therefore interesting from a dynamical systems point of view, particularly since perturbations generically can produce interactions between large numbers of modes and possibly quite complicated or even chaotic behavior. In the case when only a few modes are excited by the perturbing terms, inverse scattering provides a tool, namely soliton perturbation theory, with which to understand the dynamics of pulses when additional perturbing effects are present. Other perturbation methods, such as averaging, are also extremely useful.

Cross-disciplinary relevance for training

The benefits of a cross-disciplinary approach in research and training have been vividly demonstrated in joint ongoing nonlinear optics research performed at Northwestern. A key benefit of such close collaborations has been that both groups have had direct exposure to techniques and results that would normally be outside their area of expertise. This has been a common component of Kath's and Kumar's joint research projects. Members of both groups attend, present and discuss their work in a common setting at a weekly joint research seminar. This interaction has helped students with a mostly mathematical undergraduate training learn to discern the relative merits of various types of applied problems, and therefore which results are likely to have the most significance and impact. At the same time, students and postdocs doing experimental work have benefited from having someone available who can apply sophisticated solution techniques to theoretical models of the experiments. There is also significant overlap in the more formal instruction of the students, *i.e.* they take advanced topics courses relevant to their research programs offered both by the Applied Mathematics and Electrical and Computer Engineering departments.

In such collaborative experimental/theoretical research programs the possibilities of new developments are increased substantially by the interaction. Developing the ability to understand and take advantage of these interactions is an important part of a student's training. This aspect will be addressed explicitly in the Nonlinear Science Course (page 32); its project-based part theoretical and experimental approaches will complement each other. One of the project areas will be nonlinear optics which will greatly profit from the cross-disciplinary experience of WLK and PK.

Examples of ongoing research

An ongoing area of research at Northwestern is the study of the application of phase-sensitive amplifiers (PSAs) to optical communications. The use of PSAs in optical fibers as a loss-compensation scheme was first suggested by Yuen [33]; theoretically, these amplifiers allow a higher transmission rate for a given transmission distance because they add no spontaneous emission noise to propagating signals. The question was: does this prediction still hold true under more realistic conditions?

First, additional theoretical and numerical studies were performed by Kath (ESAM) with graduate student J.N. Kutz [34, 35] demonstrating their stability-enhancing properties. While the equation describing PSAs is very different from the NLS equation, much of its structure is inherited directly from it; this greatly aided the analysis. Parallel to such theoretical studies, experimental efforts were underway by Kumar (ECE) with graduate student G. Bartolini (now at Corning, Inc.). They showed that it was possible to actually build such PSAs, and also that they could be used in a recirculating loop to store optical pulses [36].

Most recently, the experimental work on optical phase sensitive amplification described above has been expanded to include the development of fiber-based optical parametric oscillators [37, 38]. In contrast to previous work, in this case the experimental results have preceded the theoretical. To date, only a preliminary theoretical understanding has been developed. The work was a small part of the Ph.D. thesis of M. Mills in the group of WLK (ESAM). More work is in progress.

Proposed work

Small-group research collaborations are proposed to investigate a number of new areas concerning pulse propagation in nonlinear optical fibers:

Pulse dynamics in recirculating optical storage loops and lasers

As described above, a number of recent experimental results have been obtained by Kumar's group. In particular, fiber-optic parametric oscillators have been developed and the all-optical storage of data packets has been accomplished. In addition, work is currently in progress on optical-fiber based clock recovery and regeneration. It is proposed to collaboratively investigate such devices. Both theoretical models and numerical simulations will be developed to explain the observed behavior of already constructed devices and to suggest ways to improve their performance. As part of this project, we also propose to investigate the possibility of devising new methods which can be used to obtain improved predictions of systems behavior. One of the ideas we would like to investigate is to attempt to break the pulse evolution up into two parts: the pointwise evolution inside the storage loop, and the stroboscopic evolution from one period to the next. Note that such a result, if successful, would be a PDE version of a Poincaré map. Such techniques are certainly useful for investigating the chaotic behavior of periodically forced ODEs, and the Northwestern chaotic dynamics experts (see section D.3) would contribute to this project.

Patterns in amplified optical systems

The basic equation describing pulses in a recirculating loop with amplification and filtering is the Ginzburg-Landau equation [39]. Because at high bit rates pulses are closely spaced together, it is necessary to have many pulses recirculating at any one time, and the dynamics of the pattern of pulses play an important role. It is proposed to expand the ongoing interdisciplinary interactions to now take advantage of existing expertise in pattern formation at Northwestern (see section D.1). The pattern selection behavior occurring in optical systems appears to be similar in spirit to that observed in fluid and other systems, but there are a number of differences. Nevertheless, there are sufficient similarities that indicate that such a collaborative effort will be very productive.

Novel nonlinear fibers for high bit-rate data processing

It has been known for some time that it is possible to excite Kerr solitons in Erbium-doped fiber that simultaneously are self-induced transparency (SIT) solitons for the doped 2-state atoms [40]. In addition, work has been performed which attempts to generalize the SIT soliton concept to 3-state lambda-type systems [42]. The idea is to associate an SIT soliton with each leg of the lambda transition, which then couple through the excited state. Classical effects like soliton dragging, which can be exploited for developing ultra-high speed soliton-based packet-switched communication networks operating at 100's of Gb/s rates, have been shown to occur efficiently in model 3-state systems. Therefore, it is natural to ask if the two SIT solitons can simultaneously be made to be the Kerr solitons of the host fiber that is doped with such 3-state atoms. Such pulses would allow for new types of pulse interactions in nonlinear optical fibers and could lead to new types of optical switches and memory devices.

D.5 Computational Neuroscience

Background

Nonlinearity is a common domain of operation for the brain. The central nervous system of any living creature must be capable of carrying out two major classes of operations that may be characterized as ill-posed inverse mappings; one is the class of transformations of sensory signals into meaningful perceptions, the other is the class of transformations of action goals into motor commands. An example of the former is the inverse optical problem that is routinely solved by our visual system when the two-dimensional distorted images on the retina are transformed into three-dimensional representations of the corresponding objects. In carrying out this transformation, the brain is capable of extracting stable features, such as the color and the shape of an object, out of a constantly changing pattern of physical signals. An example of the second class of mappings - from action goals to motor commands - is the inverse dynamics transformation that must be carried out to move a hand towards a target in space. This is called an “inverse problem” because the goal is to generate a nonlinear differential equation of motion for which the desired trajectory is a solution of the controlled system. Unlike its direct counterpart – the problem of determining the trajectory that results from a given equation of motion – the inverse problem admits in general multiple solutions.

Besides routinely dealing with nonlinear problems, the brain itself is made out of a large number of highly interconnected nonlinear constituents. Individual neurons receive multiple stimulations that interact in a nonlinear manner to control the membrane potential. Neurons respond to stimulation beyond a preset threshold through the firing of action potentials that are transmitted down the axons; increasing stimulation results in an increased firing rate until saturation is reached at a maximal firing rate associated with an unavoidable refractory period between the firing of subsequent action potentials. Such built-in nonlinear response has dramatic consequences for the functional properties of neuronal networks, from the possibility of synchronized oscillations and chaotic behavior in recurrent networks to the enhanced computational capabilities of layered networks designed for the implementation of sensory maps.

The functionality of neuronal assemblies is largely determined by their connectivity, as specified by the strength of the synaptic contacts. The plasticity of synaptic strengths allows for changes that occur on two different time scales: long term changes associated mostly with postsynaptic cells lead to learning, while short term changes associated mostly with presynaptic cells lead to depression or facilitation of postsynaptic activity. Efforts at understanding the dynamics of synaptic adaptation and their impact on neuronal activity incorporate crucial nonlinear effects that arise because the synaptic changes are themselves activity controlled.

Potential for cross-disciplinary graduate training

The brain uses many physical, electrical, chemical and genetic mechanisms to process sensory information, evolve concepts, formulate plans, and execute actions. Specific subsystems use specific strategies for signal processing, and a wide variety of signal transduction mechanisms facilitate interactions among subsystems. In the current model for neuroscience research, teams focus on a given subsystem and its functionality, and specialize in a narrow set of relevant tools; cross disciplinary communication is thus difficult among neuroscientists.

Computational neuroscience aims at providing a unified conceptual framework for the description of information processing in the brain, based on a synthesis of mathematical tools from statistical physics, information theory, control theory, and nonlinear dynamics. This intrinsically cross disciplinary subject brings a new approach into neuroscience research, as it searches for universal descriptions of spatio-temporal patterns of neuronal activity, based on their computational significance.

This broad approach provides a fertile environment for training young scientists in a novel and rapidly developing area of neuroscience research. The training program proposed here will result in students equipped with solid mathematical and computational tools, and capable of applying them to a wide variety of relevant neuroscience problems. Examples of current and future cross disciplinary research in this area are provided below.

Examples of ongoing research

A growing interest in complex and realistic models for **motor control** has been stimulated by advances in the field of robotics and automation, where the ability to control complex dynamical systems is necessary to achieve flexibility and fault tolerance. Recent theoretical and experimental investigations of motor behavior have highlighted that nonlinear features of the control system may provide flexible solutions to the inverse dynamics problem [43, 44]. As an example of this novel approach, FM-I has formulated a distributed model of limb control based on a combination of elementary modules, each one of them implementing a nonlinear force field acting on the limb.

A key ingredient in the translation from motor commands into desired trajectories is the existence of mechanisms for nonlinear damping (JCH). The spinal stretch reflex produces a damping force that is proportional to the velocity raised to the (1/5)th power [45]. Experimental observations suggest that this mechanism may be helpful in terminating movement, but it may also interfere with other desirable aspects of motor behavior such as fine adjustments involved in target approach and object manipulation. In the cerebellum, **pattern classification** mechanisms take advantage of nonlinear damping to generate control signals for accurate, high-velocity movements [46] that overcome long time delays in sensory and motor pathways.

Studies of human motor control suggest that the central nervous system must maintain an internal representation of the controlled limb dynamics in order to plan and execute a variety of movements. Analytic approaches have not been very successful in providing solutions to the resulting system of nonlinear dynamical equations, coupled through interaction terms between multiple moving joints. Plausible and efficient solutions have been recently obtained by means of artificial **neural networks** (SAS, FM-I) that reconstruct the complex limb dynamics by a linear superposition of predefined nonlinear functions. These networks reproduce important features of human motor learning and behavior. Neural network models consist of large arrays of highly interconnected nonlinear units that mimic the behavior of biological neurons. Such systems exhibit powerful computational abilities that allow them to implement signal processing, pattern recognition, and control tasks. In addition, these models provide a paradigm for the analysis of a variety of brain functions such as associative memory, the processing of sensory input, and motor control. Recent research advances have provided a theoretical framework to describe learning and adaptation in neural networks (SAS). The approach is grounded in statistical physics and incorporates fundamental concepts of information theory and statistical inference [47]. The formulation has been extended to a dynamical description [48] that has been applied to the investigation of a variety of learning scenarios.

A prominent topic of investigation concerns the role of nonlinear **synaptic dynamics** in the recurrent interaction between different structures of the central nervous system, such as the cerebellum, the red nucleus and the motor cortex (JCH). The emergence of symmetry, reciprocity and modularity in recurrent brain networks as a consequence of correlation driven synaptic learning [49] guarantees the existence of stable attractors in the distributed network (JCH, FM-I). Electrophysiological and anatomical data provide support to a theoretical model in which different motor behaviors are related to different attractor states of such a network [50]. The model needs to incorporate inhibitory inputs from the cerebellar cortex to regulate the sequential activation of different attractor states (JCH, SAS).

Proposed new cross-disciplinary research

A central issue in the generation of complex sensorimotor behavior is the representation of time and temporal sequences (JCH, FM-I). Recent theoretical studies [44] have demonstrated that complex patterns of coordination may be encoded by motor commands with little temporal structure, provided that the force fields generated by these commands have a sufficiently nonlinear structure (FM-I). Some of our current studies are aimed at understanding how this approach may describe the operation of multiple pattern generators within the central nervous system. A related topic (JCH, SAS) involves the encoding of serial events into spatial patterns of neural activity and the decoding of such spatial patterns into sequential motor commands [51]. The goal is to develop a theoretical framework for the representation of temporal sequences; the model needs to include a mechanism for competitive pattern recognition, a positive feedback for the enhancement of activity associated with working memory, and an overall recursive dynamical structure. The role of learning in the stabilization of this complex dynamical system remains to be elucidated (JCH, SAS).

A new proposal for interdisciplinary research is based on the results of recent patch-clamp experiments (NS). Action potentials actively invade and back-propagate along the dendrites of CA1 pyramidal neurons in a frequency-dependent manner [52]; a prolonged form of sodium channel inactivation in dendrites [53, 54] weakens the back-propagation during high frequency action potential firing. To understand the dynamics of this process, involved in memory functions through its impact on synaptic integration and plasticity, new models of sodium channels need to be developed and incorporated into current cellular models of dendritic trees (NS, WLK).

D.6 Interface Dynamics

Background

Interfaces separating two material phases occur in numerous areas of application. In fluid dynamics there are interfaces separating two fluid phases, as in thin liquid films, droplets, spreading, nucleate boiling, and the fronts separating nematic and isotropic liquid crystals. Interfaces between solids and fluids are important in crystal growth and deformable porous media. Interfaces between two solid phases are important in phase transformations in alloys and in the dewetting of polymer and crystalline films on solid substrates. In combustion, flame fronts separate the unburned reactants from the burned products of combustion. In solid-fuel combustion, in which solid melts prior to burning, there are two interfaces, the melting front and the reaction front. In addition, interfaces may separate multiphase media as when a bubbly or particle-laden fluid abuts a second fluid, in combustion involving mixtures, or in porous media. The last occurs in combustion synthesis of materials, in waste incinerators, in underground oil recovery and in living tissue. Interfacial dynamics is the controlling factor in a whole spectrum of high-technology industrial-product manufacture and simultaneously the inspiration for fundamental scientific investigation.

In all the cases mentioned above the phase interface is a moving free boundary whose shape, position, and dynamics are to be determined. Each of these represent nonlinear problems involving instability and bifurcation phenomena, wave-length selection, and chaotic behavior. The above examples exhibit the whole gamut of dynamical phenomena including coalescence and rupture, melting, freezing, sedimentation, agglomeration, chemical reactions, moving contact lines, cellular, pulsatile, dendritic and spiral patterns, chaotic behavior, and all the particular idiosyncracies of suspensions, colloids, foams, and granular or porous materials.

Potential for cross-disciplinary graduate training

Many of the analytical, numerical, and experimental techniques developed in one of the above areas are applicable in the others. The immersion of graduate students into a broad and deep study of several of these will give them a flexibility and adaptability required for our rapidly changing technical environment.

There have been a number of multi-investigator projects at Northwestern related to interface dynamics. The research described below demonstrates how new areas of investigation emerge when faculty, in groups of two or three, train students and postdocs in cross-disciplinary subjects.

Examples of ongoing research

The dynamics of **thin liquid films** are controlled by capillarity, thermocapillarity, viscous and long-range molecular forces and have broad influence on heat-transfer phenomena and devices. S.H. Davis (ESAM), Miksis (ESAM), and Bankoff (ChE), with joint students and postdocs have studied thin viscous films on substrates and the effects of surface tension and van der Waals attractions on the rupture of the films and the creation and dynamics of contact lines (see [55] for an extensive review). SHD and Di Benedetto (Math) and a jointly supervised student studied the analytical behavior of thin-film equations [56].

The dynamics of **thin solid films** are controlled by nonlinear diffusion, surface energy, and elasticity and have application to the integrity of microelectronic devices and interconnects. A pinhole in an otherwise continuous film can open and destroy the entire film coverage. SHD (ESAM), P.W. Voorhees (MSE), and a joint student studied the development of islands of crystalline film on substrates by linear and nonlinear stability methods. In addition, SHD, Miksis, and PWV with joint students and postdocs have studied solid-film dewetting of crystalline films on substrates including the effects of surface energy, surface diffusion, and elastic strains on island, and hole shapes, their contact lines and their modes of instability [57]. Further, they have examined the nonlinear evolution of whiskers and tubules. PWV [58] is also studying Ostwald ripening in the presence of elastic stresses, a process that controls the particulate size in solid-solid composites.

The **interface between solid and liquid** is the site of **phase transformation in crystal growth**, a process that for binary alloys involves a nonlinear-diffusion problem with capillarity. The morphology of the interface determines the microstructure of the solidified material, and hence its mechanical and electrical properties. SHD is studying the solidification of binary alloys including the effects of anisotropy (and hence facet formation) coupled to fluid flow, contact lines with phase transformation [59], applicable to the growth of single crystals and the development of non-equilibrium solid phases. SHD has shown that the directional solidification of a binary alloy into a long-scale convecting melt results in localized morphologies and hence localized microstructures in the crystalline solid [60]. SHD and Golovin (postdoc) have studied the nonlinear evolution of strongly anisotropic materials and the generation of facets using a convective Cahn-Hilliard equation [61]. SHD, Miksis and a joint student are studying the growth and instabilities of regular eutectics by using homogenization theory to average away the eutectic structure and obtain an equivalent directional solidification problem. P.B. Umbanhowar (PaA) and his students are setting up experiments to study the cusp formation on the top of a sessile drop solidified from below as discovered by Anderson, Worster and SHD [62]. The formation of the cusp is due to a dynamic growth angle associated with the velocity of the moving tri-junction formed at the solid-liquid-gas interface. By controlling the speed of the solidification front the shape of the frozen drop can be manipulated and a deeper understanding of tri-junction dynamics will be gained.

Liquid-solid interfaces are intrinsic to all **living tissues**. Fluid movement within the tissue (composed mainly of cells, extracellular matrix proteins, and water), along with the elastic properties of the interstitium, determines the mechanical environment of this complex material. Mechanical stresses at fluid-solid interfaces also regulate cell response, leading to matrix remodeling and ultimately an alteration in the local mechanical environment. M.A. Swartz (BME/ChemE) is studying these interactions [63] and applying them to understand edema, fibrosis, asthma, and other pulmonary diseases.

B.J. Matkowsky (ESAM), a number of colleagues, graduate students and postdocs have been studying nonlinear dynamics and pattern formation in **combustion**. Specifically, motivated by recent experimental results, Bayliss (ESAM) and BJM are investigating pacemaker target patterns and spiral patterns in gaseous combustion. In addition, they have studied the interaction of kink and cellular gaseous flame structures. Bayliss, Riecke (ESAM) and BJM have studied localized structures which travel through an underlying stationary cellular array, in their description of flames stabilized on a burner [64]. BJM and collaborators have derived in a study of more realistic reaction contexts equations for studying flames governed by sequential reactions [65].

Aldushin (visitor), Schult (student) and BJM have described the phenomenon of wave reversal in **porous medium combustion** in which reactive gas flows toward the reaction front where it reacts with the solid fuel [66]. In addition, in the same system, but under different conditions, Aldushin and BJM are investigating fingering patterns, with application to **smoldering** and an analogous fingering instability problem in underground oil recovery.

Bayliss, Ma (student) and BJM have studied heteroclinic cycles in a reactive Rayleigh-Bénard problem, with applications to **combustion synthesis of materials** and smoldering. Volpert (ESAM) and BJM derived nonlocal equations for the amplitude of counterpropagating combustion waves and investigated the effects of nonlocality in a **solid fuel combustion** problem applicable to combustion synthesis of materials; they have also described conditions for the appearance of spiral patterns in solid fuel combustion [67]. Bayliss and BJM are currently investigating the interaction of counterpropagating temperature pulses (hot spots) that occur in solid fuel combustion. When the pulses meet, their interaction can, at one extreme, lead to their complete annihilation, and at the other extreme, they can pass through each other essentially unaffected, as is the case for solitons. The goal of the current investigation is to describe the transition between the two extremes.

Proposed new cross-disciplinary research

A new area of interest will be the merging and coalescence of positive and negative phospholipid bilayer vesicles. Here the experience of SHD and Miksis on thin films will be brought together with the experimental biophysical methodologies for studying membranes. To treat the membranes as thin films new physical/electrical properties and certain non-continuum features have to be taken into account.

SHD, Golovin, BJM and Nepomnyashchy will shortly begin a U.S.-Israel Binational project on the interaction of flames and flame-grown diamond films. This effort will bring together recent studies on kinetically controlled phase transformation and combustion for the design of diamonds with predictable microstructures.

Another promising direction for cross-disciplinary research will be provided through collaboration with Volpert (ESAM) and his students who are investigating frontal polymerization, a new technological process in which monomers are continuously fed into a reactor and converted into the desired polymers in an interface separating monomer from polymer. The frontal polymerization process offers advantages over conventional technologies.

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E Other Research

E.1 Packing of Granular Media

Granular media are composed of discrete solid particles, yet they exhibit completely different bulk properties than their constituent material (see section D.2). Although particulate systems are of great importance in many commercial enterprises (*e.g.* pharmaceuticals, oil refining, food processing, construction, *etc.*) and provide conceptually simple model systems for flux motion in semiconductors as well as for dynamics in other "jamming systems", there exists little quantitative understanding of their behavior [1, 2]. The main reasons for this difficulty stem from the disordered arrangement and highly nonlinear interaction of the grains and the intrinsic inability of this complex system to relax to the state of minimum energy [3]. P.B. Umbanhowar investigates granular pattern formation (see section D.1) and static/quasi-static behavior in granular assemblies. His research in the latter area focuses on two exciting developments in our understanding of granular media. The first concerns the important role heterogeneous networks of load carrying grains or "force-chains" play in distributing stress. The second is the discovery of complex dynamics associated with packing in vibrated grain piles. PBU, with undergraduates T. Bay and B. Hammelman, investigates the spatio-temporal evolution of stress-chains and their dependence on packing density. In one experiment, a tube of sand is packed or expanded by gentle shaking. A sensitive force sensor in the bottom of the tube reveals the global influence of stress-chains and enables statistics to be gathered on how the force-chains change in time and as a function of packing density. Comparisons with discrete and continuum models are helping to reveal the properties of these materials. In the other complementary experiment, a new optical technique for measuring forces at the surfaces of the container is being used to study the microscopic rearrangements of force-chains.

E.2 Small Dynamical Systems

Consider a small system composed of discrete elements. It is expected that as the number of elements of the system increases, the discrete-system behavior can be formulated in terms of a continuum description. But, how large must a small system be in order to show continuum behavior? To answer this question, S. Lichter (ME) and collaborators have been investigating a 1-d chain of point masses coupled by nonlinear springs [5]. Using Fermi-Pasta-Ulam recurrence as a measure [6], the system's approach to continuum behavior can be monitored. Discrete systems begin to show continuum behavior as the number of elements increases and as a second parameter, which accounts for energy density and nonlinearity, decreases.

The dynamics of discrete objects in non-equilibrium systems is a generic phenomena that occurs in many disciplines and is of interest from both a practical and a theoretical point of view. This work is intrinsically interdisciplinary: it was motivated by previous work by SL on how liquids spread [7]. This spreading is controlled by molecular forces within the small region surrounding the moving contact line. Modeling this region involves techniques from Hamiltonian dynamics and KAM theory. This work interfaces with that of

Cvitanovic's group in physics and would benefit from their expertise in characterizing chaos, diffusion, and ergodicity (section D.3). On the training side, this work offers a natural entry point for students to begin studying nonlinear systems. The 1-d nonlinear chain is a simple system on which to explore many of the techniques of nonlinear dynamics such as the transformation from physical space to phase space, Hamiltonian dynamics, measures of chaos and entropy, and numerical procedures suitable for long-time simulation. This work also offers a simple introduction to the links between micro-scale discrete dynamics and macro-scale modeling. In ME, there is an increasing need to understand how macroscopic properties of materials depend on their microstructure, for example, in fluid mechanics (complex fluids, fluids with structure) and solid mechanics (crack propagation, materials with inclusions). Introducing techniques well developed within the Physics community into ME would help prepare mechanical engineering students in designing the next generation of materials. The needed course development and joint-advising of students would be greatly aided by this grant.

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F Education and Training

The need for a strong foundation in the analysis of nonlinear dynamical systems is common to many graduate students in natural science, engineering, and mathematics. The goal of the proposed training program in nonlinear science is to provide these students with (1) the basic mathematical and computational tools, as well as intuition, for tackling nonlinear problems, (2) research experience in mathematical modeling and analysis, and computational and/or laboratory experimentation, (3) the special communication skills required to effectively apply these research tools and experiences to cross-disciplinary basic and applied research projects, and (4) an appreciation for the spectrum of basic to applied research, and appreciation of diversity's benefits to the workplace. In addition to these specific integrated training objectives, the proposed program ensures in a direct, concerted fashion that every graduate student gain, early on, basic research and communication skills, *e.g.* literature search, critical reading of both theoretical and experimental research papers, preparing both oral and written technical reports. In order to achieve these educational goals we propose a number of training activities, detailed below. From the initial welcoming retreat, through the second year intensive project-driven course, the internships, the on-going seminars and workshops, and the ultimate emphasis on co-advised, cross-disciplinary thesis projects the training program is designed to instill a spirit of cross-disciplinary research that the students will carry with them into the industrial, governmental, and academic workplaces.

The scale of the proposed program, which involves students and faculty in different departments and different schools, will be made possible initially by IGERT funding. This new cooperation in graduate education, which intertwines the two primary activities of a faculty member – research and teaching – will lead to better integrated graduate training and to research programs with broader scope.

F.1 Course of Study

Here we provide a brief overview of the training program. The individual components are described in detail in the next section. The chronology and connectivity of the program is summarized in schematic form in Fig. 3.

We plan to recruit approximately seven new students to the program each year; these new students will be introduced to the other student and faculty participants and to their **Nonlinear Science Advisor** (page 32) at a **Welcoming Retreat** (page 32). As first year students they will take core courses required by their respective departments, as well as individually selected electives in a preparatory Nonlinear Science sequence. Right from the beginning all students will gain exposure to current research through the **Cross-disciplinary Nonlinear Science Seminar** (page 36) and the student–run **Graduate Student Seminar** (page 36). As appropriate, the students will also participate in the **Women in Science Seminar** (page 36). During their first summer the students will work on a small scale **Summer Research Project** (page 32). Departmental course work will continue during the second year, in parallel with the intensive year long **Nonlinear Science Course** (page 32), which forms the core of the proposed program. It is comprised of an initial lecture–based part and

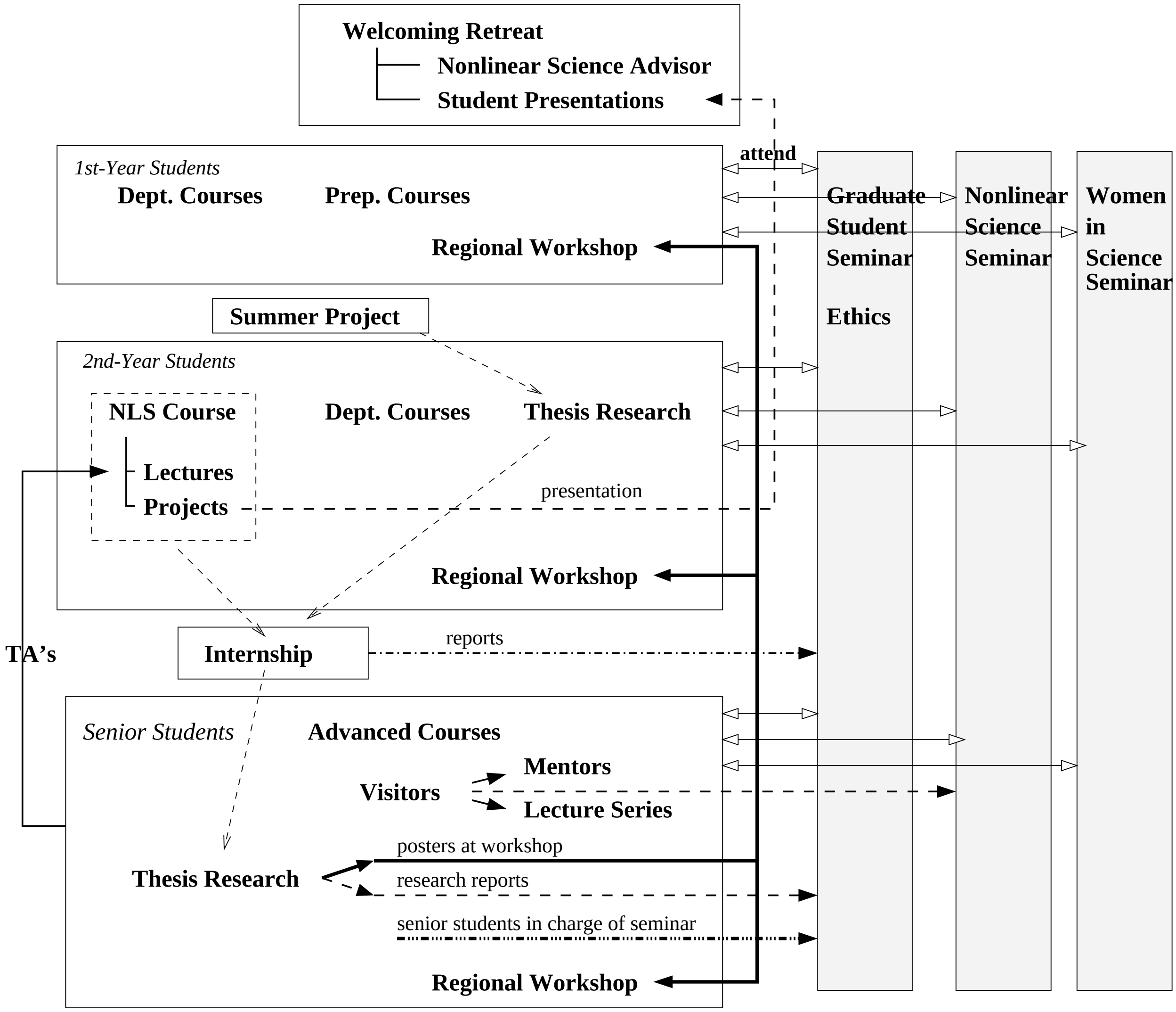

Figure 3: Chronology and connectivity of the study program.

a subsequent project–focussed part. Thesis research becomes the students' primary activity by the third year; the proposed program encourages **Dual Advisor Thesis Projects** (page 36). Senior graduate students will be expected to complement their thesis research by a 3-6 month **Internship** at a government or industrial lab or at another University (page 34). Lectures within the **Visitor Program** (page 37) and a yearly **Regional Workshop** (page 37) will provide further exposure to current research. Senior graduate students will present their research at workshop poster sessions. Care will be taken to ensure that the average time-to-degree is not longer for the IGERT students than for the more traditional students (page 37).

F.2 Training Program - Description of Specific Components

1. Welcoming workshop retreat: The incoming graduate students will be introduced to the Nonlinear Science Program during a weekend retreat to take place in the early fall, before the first week of classes. On this occasion the new students will meet the faculty and graduate students associated with the program. The main purpose of this meeting is to bring the incoming students into the Nonlinear Science Program community and give them an overall view of the scientific activities of the program. Presentations will be given by the senior graduate students, who may report on the results from their work during the second-year project course, from their internship, or from their thesis research. In addition, the retreat will provide an informal setting for the discussion of general topics of concern and interest to scientists. It is also a natural setting for establishing student-mentor relationships, as well as identifying a suitable Nonlinear Science Advisor for each student.

2. Nonlinear Science Advisor: This faculty member, typically outside the student's own department, oversees the students progress through the Nonlinear Science Program. Initially, the Nonlinear Science Advisor helps the departmental advisor direct the student's course of study, with special attention to the background courses needed for the intensive second year course. As the student progresses through the program, the Nonlinear Science Advisor's role shifts from that of an advisor on courses to one of a mentor who takes an interest in the student's development as a scientist.

3. Summer Project: During the summer between the first and second year students will work on small-scale research projects with members of the Nonlinear Science Program. Since the students will be on the Nonlinear Science Program Fellowship and will not require support by a goal-oriented grant of a specific faculty member, this project can be exploratory for both the student and the faculty member and will allow the student to get a better feeling for an area of research before he/she decides to start a thesis in it. The summer research projects will also involve 2-3 advanced undergraduates from underrepresented groups to aid us in identifying and recruiting talented students to our training program (see section 3.G, page 40).

4. Cross-disciplinary Nonlinear Science Course: The centerpiece of the proposed graduate training will be the cross-disciplinary nonlinear science course based on teaching across departments and schools and on student research projects. This year–long intensive course, intended for students in their second year of graduate study, will constitute one of the students' elective courses in their respective Ph.D. programs. It will be taught by faculty from the Weinberg College of Arts and Sciences, the McCormick School of Engineering and Applied Science, and the Northwestern University Medical School. The participating graduate students will be recruited primarily from departments of applied mathematics, mathematics and physics, the Northwestern University Institute for Neuroscience, and a number of engineering departments (biomedical, chemical, electrical and mechanical engineering, and material science). The course will provide the students with an in–depth, integrated treatment of different aspects of nonlinear science, while also introducing concrete examples of important nonlinear processes in diverse systems. It will equip the students with the necessary tools for investigating nonlinear systems in their specific field of interest.

The course will start with lectures by one or two faculty members and supplemented by review sessions on background material which are led by senior students in the program (Fall quarter). It will cover in particular the qualitative behavior of dynamical systems described by ordinary differential equations and maps, including fundamental elements of bifurcation theory, low-dimensional chaotic dynamics, and an introduction to dynamical systems with many degrees of freedom.

In the Winter and Spring quarters the students will split into 2-3 project-focussed teams comprised of approximately 5 students each and supervised by 2 faculty members with complementary expertise and perspectives. Examples of research areas from which the themes for the projects will be chosen are listed below. The students in a given team will focus on one theme, with each student pursuing his or her own project as part of the larger group effort; this ensures that each student learns all aspects of a specific area, while still gaining valuable team-work experience. For example, some students may set out to reproduce theoretical results of research papers in the literature, with the ultimate goal of adding their own contributions to the topic, while other students may read and critique experimental papers, before going on to do laboratory work related to the team research theme. Progress in nonlinear science rests on the close interplay among theory, experiment, and computation. This will be reflected in the course by including a strong computational component in each student's experimental and/or theoretical project.

Background material that is relevant to all students in a team will be addressed in weekly group meetings; the role of discussion leader will rotate among the students and faculty in the group. In these meetings the students will also briefly report on progress in their work and on possible difficulties. This gives the students ample opportunity to practice their presentation skills and to incorporate the feedback they receive from their fellow students and the mentoring faculty in preparing their final project presentation.

In addition to the weekly meetings of the teams, there will be a weekly meeting of all students and faculty in the Nonlinear Science Course. There will be one primary faculty member who will coordinate this aspect of the course, although responsibility for the common lectures will cycle between the groups. Initially, for instance, the faculty may take a lead in the class meetings by giving some overview lectures of their team's research area. As the students progress in their own work, they will start presenting the highlights in the style of a journal-club presentation. These presentations will provide the background for the capstone of the course: the final presentations by the students in each of the teams. A class discussion following each presentation will give students valuable feedback that they can take into account in preparing their final written project report.

Particularly successful projects, which may continue through the summer, will be presented at the welcoming retreat for the new student participants the following fall. Since the project themes in the Nonlinear Science Course change from year to year, graduate students may find it profitable to participate in the project–part of this course more than once.

The course will give the students basic training in conducting research: literature search and study, reproducing other researchers' results before trying to extend them, discussing results with colleagues, giving and receiving critique, formal written and oral presentation.

Moreover, the course 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, thus developing communication skills that will prove invaluable in future careers in industry or academia.

A sample list of themes for the projects part of the course:

A. Neurocontrol of Biomorphic Systems: The projects will combine concepts and tools of theoretical neurocomputing and nonlinear adaptive control in nonlinear limb dynamics, and apply them to the control of a biomimetic robotic system in the lab of Prof. Mussa-Ivaldi.

B. Solitons and Solitary Structures: The projects will focus on localized structures in optical and other physical or chemical systems. Students will set up experiments on soliton propagation in optical fibers in the lab of Prof. Kumar. Comparison with theory will involve numerical simulations of the corresponding analytical models of nonlinear pulse propagation. The behavior of nonlinear waves in optical systems will be contrasted with their behavior in other physical and biological systems.

C. Pattern Formation: Students will investigate pattern formation in physical, chemical, or biological systems. This could be waves in excitable media (e.g. in the heart, neurons, EEG-activity) or wave patterns in periodically forced systems (e.g. surface waves on liquids or granular media). The investigations will include experiments in the lab of Prof. Umbanhowar.

D. From Low- to High-Dimensional Chaos: Each project will require mastery of the same basic set of techniques of the theory of low-dimensional chaotic systems, including computation and graphical visualization. An experimental physicist might use the theory to compute conductance fluctuations in a microdot, while a physiology student might analyze chaotic data from a neurophysiological experiment. Others may use numerical computations to investigate spatio-temporal chaos, or perform experiments on mixing in the lab of Prof. Ottino.

5. Internship Program: To complement their thesis research students will be encouraged to participate in an internship program. The goal of this program is to provide the students with supplementary training that will significantly broaden and strengthen their education. For example, students working on theoretical projects might intern in experimental labs, while students working on experimental theses might collaborate on theoretical or computational projects. In other cases the internship could allow the student to master a specific experimental technique or theoretical approach not readily available at Northwestern, but important for the student's thesis research.

Students, together with their advisors, will make the initial contact with the internship host. A brief proposal will then be written that clearly states the goals of the internship. We expect that internships will last 3-6 months. The experience of the hosts chosen for the internship program shows that this length of time is usually sufficient to achieve meaningful results and sometimes even form the basis for a publication. After the first three months the host in agreement with the thesis advisors will decide whether the project is successful and whether the internship will be extended to the full six months. Upon returning to

Northwestern the student will present his/her results in the form of a written report and a brief presentation in the Graduate Seminar Series.

The internships will make use of the extensive connections the Northwestern faculty have with other institutions and labs. Close contact between the thesis advisors and the student's host will contribute substantially to the success of the internships. At the same time the internships will provide opportunities for these contacts to grow into full-fledged collaborations.

We have contacted a number of potential hosts to get their input on our planned internship program. They have expressed their interest in participating; several representative letters of commitment are appended to the budget justification. Here we give a brief description of some of the proposed hosts; others will be contacted, pending IGERT grant award.

G.B. McFadden, N.I.S.T. Computation and analysis on a broad range of solidification theory with close links to experimentalists in the Metallurgy Group at N.I.S.T. McFadden has worked closely with both Davis (ESAM) and Voorhees (MSE).

R.E. Ecke and R. Mainieri, Los Alamos National Laboratory. Experiments on pattern formation in fluids. Theory - nonlinear dynamics, statistical mechanics of chaotic systems.

M. Sheppard, Schlumberger Cambridge Research. Research on multiphase flow in pipes and flow of complex fluids in porous media with applications to oilfield research. Will provide students with exposure to industrial research.

D. Choudhury, G. Luther, M. Gildea, Corning Inc. Researchers in Corning's Process Engineering and Modeling Group, familiar with the simulation of lightwave components and systems. Will provide useful exposure to nonlinear dynamics in an industrial setting.

J.P. Gollub, Haverford College and U. Pennsylvania. Leading experimentalist in nonlinear dynamics and pattern formation. A strong advocate of undergraduate education, track record of advising successful research by undergraduates; particularly stimulating for future educators in undergraduate institutions.

E. Bodenschatz, Cornell U. Experimentalist working on pattern formation, nonlinear dynamics and turbulence. With a Ph.D. in theoretical physics he is particularly well suited to help students bridge the gap between experimental and theoretical work.

M. Dennin, U. California Irvine. Experimentalist working on electroconvection of liquid crystals and on thin films.

S. Nagel, U. Chicago. Experience with taking theory students into laboratory work on hydrodynamic instabilities and granular materials.

I. Rehberg and L. Kramer, U. Bayreuth, Germany. Large laboratory with students working on pattern formation, dynamics of granular media and complex fluids. Theory of pattern formation, spatio-temporal chaos, complex fluids. Close collaborations with Riecke (ESAM).

T. Bohr, C. Ellegaard, M. Levinsen, M.H. Jensen, H. Bruus, J. Hertz, and A. Jackson, Niels Bohr Institute and Nordita, Copenhagen, Denmark. A group of theorists and experimentalists with expertise in physics of complex systems ranging from neuronal activity to quantum chaos.

6. Dual Advisors: Student's thesis research will be **co-advised** by a pair of faculty members. The general thesis area, identified during the student's second year, is elaborated on by the student in a proposal to the Executive Committee (see section H) for continued IGERT fellowship support. The exercise of writing such a proposal, which requires a literature search and a thoughtful formulation of the thesis topic, will in itself be a valuable educational experience for the student.

7. Graduate Student Seminar Series / Ethics in Research: This new seminar series will be organized and directed by the graduate students, with the aid of one faculty mentor. Faculty will be discouraged from attending this seminar. This format will serve a number of important functions: uninhibited by the presence of faculty, the students will have the opportunity to have active discussions on both scientific and career-oriented subjects; the discussions will give the student speakers feedback on their presentations and thus strengthen their communication skills; the students will have the opportunity to learn about the research results of other students. Extensive discussion will be the hallmark of this series; experience shows that an attractive format for the seminar is to hold it late in the day, with follow-up discussion over pizza. This seminar will be allocated a small yearly budget from the institutional matching funds to cover operational expenses.

At least once per quarter the selected topic for discussion will relate to issues of ethics in research and the role of diversity in the workplace. For this component of the series, the faculty mentor will suggest speakers with backgrounds in the government or private industry who have strong interests and personal experience related to these issues. In organizing these special meetings of the Graduate Student Seminar, the students may also consult representatives from Northwestern's administration who have institution-wide responsibilities for dealing with ethics in research and the role of diversity in the workplace. (For example, the Office of the Vice President of Research oversees all aspects of ethics in research; the Office of Minority Affairs in the Graduate School and the Minority Engineering Opportunity Program in the McCormick School of Engineering are two of many offices throughout the University that address diversity issues.)

8. Women in Science Seminar: To aid retention efforts, a Women in Science seminar series will bring women graduate students, postdocs, and faculty together on a regular basis, providing a natural forum for mentoring. This seminar series is described in section 3.G, page 40.

9. Cross-disciplinary Nonlinear Science Seminar: This weekly seminar series, initiated in January 1997, has drawn a wide attendance from applied mathematics, physics and a number of engineering departments at Northwestern. The titles of the ~ 80 seminars given so far are available on `www.phys.nwu.edu/~canis/`. To date this series has been financed through contributions from the research grants of the participating faculty members. Institutional matching funds for the proposed IGERT program and the Northwestern University Nonlinear Science Institute will enable us to increase the number of out-of-town speakers substantially. The scope of the seminar will be broadened to include more engineering and biological applications. In addition, researchers from industry will present their nonlinear problems, giving the students a direct exposure to industrial applications.

In order to enhance the educational impact of this research seminar and to integrate it into the IGERT training program, the speakers will be asked to give an informal, 15-minute introductory presentation prior to their official seminar. By separating this presentation from the main seminar it will be easier for the presenter to adjust the level of presentation to the level of the students (and other non-experts). To facilitate further discussions among students, faculty members and the speaker there will be a coffee after the seminar.

When appropriate, we will use the video-teleconferencing capabilities available at Northwestern, with seminars transmitted interactively between the Evanston campus and the medical school. We plan to extend the video-teleconferencing to the U. of Chicago, where there is interest in participating in our Nonlinear Science Seminar series, and, conversely, their seminars *Computations in Science* and *CAMP/Nonlinear PDE's* are of interest to us.

10. Regional Nonlinear Science Workshop: A yearly cross-disciplinary workshop on nonlinear systems will be organized jointly with U. Chicago and other universities in the midwest (*e.g.* Notre Dame, University of Illinois-Chicago and Urbana-Champaign, University of Michigan). This one-day meeting will further the interactions between the research groups that work on nonlinear systems - both within Northwestern as well as between the universities in the region. About six speakers will showcase recent interesting research coming out of the participating universities. In addition, three leading external researchers will be invited to give an overview of recent important work in their field; their travel expenses will be covered by the Institutional matching funds to the proposed IGERT program. A poster session with snacks and drinks in which students present their results in an informal way will be an integral part of the conference, providing an opening for discussions among the participants. Four small scale workshops organized with U. Chicago have already taken place (see `www.phys.nwu.edu/~canis/`).

11. Visitor Program: An active visitor program will bring to Northwestern University visitors whose research impacts a number of faculty participants, and who have demonstrated potential as external mentors to graduate students. The program will contribute to promoting and maintaining national and international, academic and industrial collaborations with a strong base at Northwestern. It will also give us another route to achieving the desired diversity within our program. In addition to technical research seminars, the IGERT funded visitors will give introductory lectures on their research field to all Nonlinear Science Program students and interested faculty. Informal get-togethers will encourage further interactions between the students and the visitors. The visitor program will be made possible by University matching funds to the IGERT grant.

12. Time-to-Degree: The proposed Fellowship program can be implemented without lengthening the average time-to-degree for Ph.D. students at Northwestern. The overall plan is twofold: 1) course work and group projects in nonlinear science are substituted for elective courses in the various departments, and 2) fellowship support, combined with the close mentoring and continuous feedback from the Nonlinear Science Advisor and thesis advisors, will allow students to focus on their thesis topics more quickly and to efficiently incorporate their internship experience within their thesis research.

We illustrate this by the program as implemented for physics graduate students. In their first two years, graduate students in physics at Northwestern normally take classes in the following sequence:

1st year	**Fall**	**Winter**	**Spring**
	Math Physics I	Math Physics II	physics elective
	Quantum Mechanics I	Quantum Mechanics II	Quantum Mechanics III
	Statistical Physics I	Electrodynamics I	Electrodynamics II
2nd year	**Fall**	**Winter**	**Spring**
	Quantum Field Theory	Particle Physics I	Statistical Physics II
	Solid State Theory I	Solid State Theory II	physics elective
	astrophysics elective	physics elective	astrophysics elective

The corresponding curriculum for students in the Nonlinear Science Program will be:

1st year	**Fall**	**Winter**	**Spring**
	Math Physics I	Math Physics II	<u>nonlinear preparatory</u>
	Quantum Mechanics I	Quantum Mechanics II	Quantum Mechanics III
	Statistical Physics I	Electrodynamics I	Electrodynamics II
2nd year	**Fall**	**Winter**	**Spring**
	Quantum Field Theory	Particle Physics I	Statistical Physics II
	Solid State Theory I	Solid State Theory II	<u>nonlinear elective</u>
	<u>Nonlinear Science I</u>	<u>Nonlinear Science II</u>	<u>Nonlinear Science III</u>

The Nonlinear Science Course (described above, page 32) is a unique blend of lecture-based and project-based learning. Substitution of this sequence for some physics electives will provide ample time for students to complete all required physics classes and still participate fully in the Nonlinear Science Program.

As teaching experience is an essential part of any graduate education, most IGERT Fellows will be asked to teach for one or two quarters in their first year. Normally, graduate students in physics or astrophysics at Northwestern are supported through their second year by Teaching Assistantships. They are expected to 1) complete their required course work, 2) spend about 12 hours per week on their teaching duties, and 3) begin searching for a thesis project. Currently the workload from classes and teaching is such that most students do not make much progress toward a thesis project during the second year.

By contrast, second-year IGERT Fellows will have the benefit of no teaching duties, close mentorship, and the research-integrated Nonlinear Science Course. We expect that they will not only be ready to begin thesis research during the second year or by their second summer but also have well-defined ideas about what kind of internship will be most useful to them in gaining essential background necessary to complement or strengthen their thesis research. We thus expect that IGERT Fellows in physics will have a comparable time-to-degree with other students in physics.

The Ph.D. programs in departments other than physics will be harmonized with the Nonlinear Science Program in a similar fashion.

F.3 Preparatory and Topical Nonlinear Science Courses

Here we provide a partial list of courses currently offered at Northwestern which may serve as preparatory or advanced Nonlinear Science Program courses. A more complete description is available on `www.phys.nwu.edu/~canis/`. The new Nonlinear Science Course, made possible by the IGERT Nonlinear Science Program is described in section F.2.

At present the courses are designed and scheduled within individual departments. One of the important effects of the cross-departmental nature of the IGERT Nonlinear Science Program will be to harmonize the curriculum across the three participating schools. In this, the fact that we have the enthusiastic support of the chairs of all of the participating departments is critical.

Course acronyms indicate the level: C = advanced undergraduate, D = graduate, E = advanced study seminars. The key to departmental abbreviations is given on page 2.

Preparatory Courses: Students who have not had an introduction to nonlinear dynamics may choose one or more of the following courses, depending on their background, to take during the first year of graduate study:

- ESAM C22 *Applied dynamical systems* (introductory survey of nonlinear dynamics)
- Math C03 *Differential equations* (emphasis on qualitative view point)
- Math C13 *Chaotic dynamical systems* (rigorous treatment of dynamical systems)
- ECE C75 *Nonlinear problems in engineering* (Engineering-oriented introduction to dynamical systems)
- PaA D60 *Introduction to nonlinear dynamics and chaos* (Graduate level introduction to nonlinear science)
- ESAM D21 *Models in applied mathematics* (3-quarter introduction to mathematical modeling)

Advanced courses: A selection of more specialized courses relevant to the program:

- ESAM D12 Methods of nonlinear analysis
- ECE D06 Nonlinear optics
- ME D29 Turbulent flows
- ME D34 Random data and spectral analysis
- PaA D60 Introduction to neural computation
- PaA D60 Advanced topics in statistical mechanics
- PaA D16-2 Diffusion, transport and non-equilibrium statistical mechanics
- ESAM D31 Nonlinear wave propagation
- ESAM D42 Stochastic differential equations
- ME D60 Advanced engineering dynamics
- Math D47 Dynamical systems
- Math E15 Advanced seminar in dynamical systems

G Recruitment and Retention

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 Northwestern University Institute of Neuroscience.

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 H 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 Northwestern and continues until the student completes the Ph.D. (see section 3.F.2).

The program will be advertised in three primary ways: (1) through the participating departments graduate program brochures and webpages, as well as on the Northwestern University Nonlinear Science webpage `www.phys.nwu.edu/~canis/`, (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 newsletters, 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 Northwestern University, 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 Nonlinear Science Program.

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 underrepresented 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 Nonlinear Science Program 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 Nonlinear Science Program 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 K). Each undergraduate will be assigned a Nonlinear Science Program graduate student who will serve as a "junior mentor". Minority students will also participate in the activities of Northwestern's summer "Minority Research Opportunity Program" 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 Nonlinear Science Program benefits by establishing a relationship with strong prospective graduate students.

- **Mary L. Cartwright Graduate Fellowships**
We shall establish new special fellowships to which we shall attract one or two promising women or minority students per year for the duration of the program. These special fellowships, named for the mathematician who discovered in the 1940's many of the phenomena today known as "chaos", will guarantee two years of support(with the possibility of renewal) and be accompanied by a substantial yearly travel allowance to encourage visits to other institutions and/or attendance of conferences. From the time the Cartwright Fellows begin their graduate training until they obtain their Ph.D. degrees, they will be paired up with a mentoring faculty member with a strong interest in the support and education of women and minority students. The mentor will meet frequently with the fellow, monitor his/her progress towards the completion of the Ph.D. program, provide advice on educational and research opportunities, and offer support and help to overcome difficulties that, natural as they may be within the process of obtaining an advanced education, tend to have a magnified negative effect on women and minority students.

- **Women in Science Seminar**
In order to address the issue of recruitment and retention of women in the graduate programs in science and engineering, Professors Silber, Solla, Swartz and Wilkinson propose to initiate and foster a "Women in Science" group at Northwestern University. Women in their senior undergraduate, graduate, and postdoctoral years will be invited to join a monthly lunch seminar together with women faculty in sciences and engineering. The format of these informal meetings will be a presentation by a student followed by a general discussion of the topic of the seminar. The discussion will also include other scientific issues of common interest, and professional problems that affect the effectiveness and performance of women in science and engineering. The goal is to provide a friendly, nurturing environment for women students to develop their skills as seminar speakers, and to encourage them to discuss scientific topics that might have attracted their attention, whether or not directly related to their

own research. The meetings will encourage the participation of women in physics, mathematics, applied mathematics, chemistry, biology, and a variety of areas in engineering and medicine, thus creating an interdisciplinary environment that will expose the participants to a variety of topics and techniques of interest in current scientific research. Experience from places where such programs have been in place over many years demonstrates that such a group provides not only a fertile ground for the exchange of scientific information and the establishment of interdisciplinary networks, but also a supportive and nonthreatening environment where younger women are able to candidly voice their doubts and aspirations. The presence of older, professionally established women provides an invaluable source of advice and encouragement, beyond their obvious role as models.

Examples of IGERT Nonlinear Science Program Faculty Mentoring Experience

Professors Silber and Solla have considerable combined experience with recruiting and mentoring of under-represented groups in the sciences and engineering. Here we briefly describe some of their past activities in this area. Other participating faculty have expressed a strong interest in serving as IGERT fellow mentors.

- **Mary Silber** takes an active interest in the progress of women and minority applied mathematics students at Northwestern and has also been invited to mathematics departments at other universities to give special colloquia and to meet with the women graduate students. She has served on a panel discussion sponsored by the Association for Women in Mathematics (AWM) at the largest annual professional meeting of mathematicians in the U.S. (the January joint AMS/MAA meeting). The panel discussion, on issues related to launching a career in the mathematical sciences, was subsequently written up for the AWM newsletter. Professor Silber has helped organize informal get-togethers for the women at various conferences, including the Snowbird SIAM Dynamical Systems Conference, which she has co-chaired. Silber served as a consultant for the Mathematical Association of America's Project NExT, where she mentored recent mathematics Ph.D.'s in their first years of a faculty position.
- **Sara A. Solla** was active as recruiter and mentor for the AT&T Bell Laboratories Graduate Research Program for Women during her 10 year tenure as an AT&T Bell Laboratories staff member. This program, which supports women through their Ph.D. studies in all areas of science, has had a high degree of success, as measured by an almost 100% retention rate. It has been a particular source of satisfaction to Professor Solla that the three women that she brought into her group at Bell Laboratories, and collaborated with in the early stages of their careers, have gone on to staff positions at AT&T and all three have established themselves successfully in the research community.

H Organization and Management

The proposed IGERT program will provide the core of the graduate training (section 3.F) in the planned Nonlinear Science Institute at Northwestern University. This Institute will begin operation in Fall 2000, pending support through this NSF IGERT program. The University will provide substantial seed money for graduate fellowships, workshop and seminar series visitors and administrative/technical support. The Institute will further enrich the graduate training environment through the presence of postdoctoral fellows and senior visitors. The IGERT program will be administered by the Directors and Executive Committee of the Northwestern University Nonlinear Science Institute. The PI and co-PI's of the IGERT proposal are responsible for the accounting, scientific activities and research program.

The Directors

The proposed directors of the IGERT program are P. Cvitanović (PaA) and S.H. Davis (ESAM). Prior to joining the Northwestern University faculty, Professor Cvitanović built up and directed the Center for Chaos and Turbulence Studies at the Niels Bohr Institute, Copenhagen, a successful interdisciplinary effort involving approximately 20 researchers and 20 graduate students. Professor Davis has a long and distinguished record of directing interdisciplinary research and graduate studies at Northwestern University, through his individual research efforts and also during a three-year directorship of the Multiphase Flow Center at Northwestern University. The two-director leadership, patterned after the Max-Planck Institutes model, brings the complementary strengths of the proposed directors to the program, while emphasizing the interdisciplinary character of the Nonlinear Science Institute.

During the absence of either director the other assumes full responsibility for the operation of the Nonlinear Science Institute. In case of temporary absence of both directors, a deputy director would be appointed to supervise day-to-day activities.

Either director can appoint additional Northwestern University or external faculty to be a one-year Associate Member of the Nonlinear Science Institute. After a year, such appointments would lapse, unless either director deems the activity of the Associate Member to be of sufficient importance for the Nonlinear Science Institute to merit promotion to a Member.

Executive Committee

The day-to-day training, research, communications to participants and other activities of the program will be supervised by the Executive Committee. The Executive Committee will consist of *ex officio* the two directors and the other three co-PI's on the IGERT grant. An additional faculty participant representing an area otherwise not represented by the Executive Committee and a graduate student in the Nonlinear Science Program will be appointed to the committee for one year terms.

The Executive Committee will meet prior to the start of each academic year, and then at least once per quarter during the academic year. The meeting chair will alternate between the two directors. Depending on the agenda, other faculty participants, or external experts may be invited by either director to take part as non-voting members. Points can be introduced to the meeting agenda by any IGERT participant, as well as by the graduate students' representative. The secretary is responsible for the minutes and their timely distribution to the Nonlinear Science Institute members.

The Executive Committee appoints, each year, a faculty member and/or a graduate student to run each of the seminar series, and another pair to organize the retreat and regional workshop. In each case, the seminar/workshop budget is set at the outset by the IGERT budget and University matching funds.

After the third year of the program, there will be a comprehensive external review. The review panelists will consist of members appointed by NSF and senior invitees from other instituions.

The Executive Committee discusses and proposes the allocation of IGERT program resources, as described below. Daily expenditures, travel grants and the short term visitor reimbursement are approved by either of the two directors. The two directors' agreement is prerequisite to granting graduate fellowships, purchase of instrumentation, equipment or other expenditures exceeding in total $8,000.

Allocation of Resources

The resources allocated by the Executive Committee:

- **Fellowships for incoming students**. One participating IGERT program faculty member per department (listed in section B) will be responsible for identifying potential graduate students for the program in the departmental applicant pool. In addition, prospective students may express their interest in IGERT directly to the program. The Executive Committee will review the applications, and any supplementary materials provided by the applicant's home department. Acceptance decisions will be made shortly after the decisions by the individual departments, in order that the IGERT and departmental fellowships be effectively combined into attractive recruiting offers. Typically, the first nine-months of a student's graduate study will be supported by departmental fellowships, with support through the student's second year of study guaranteed by an IGERT fellowship (provided the student remains in good academic standing).
- **Fellowships for continuing students**. After their second year students are eligible for continuing IGERT fellowships. The prime condition for this eligibility is a co-advised, cross-disciplinary thesis project, as described in section 3.F.2. The student will write a brief proposal, accompanied by his or her advisors' letters describing the interdisciplinary nature of the project and relation of the project to nonlinear science. Decisions about the continuing fellowships, which typically begin in the Fall, will be made each Spring in order to give the students and their advisors ample time for planning.
- **Internships**. Students are encouraged to apply for internships, as described in section 3.F.2. The student's proposal will explain his or her choice of group, and outline the research topic to be investigated with particular emphasis on the research perspectives gained that are not available locally. The student, together with his or her

advisors, is expected to have established the contact with the prospective host and secured an invitation.

- **Visitors program**.
  To ensure the cross-disciplinary impact of the visitor program, applications for visitor funding will be filed jointly by faculty members in different departments. Priority will be given to visitors willing to give introductory lectures of general interest to Nonlinear Science Program graduate students and researchers. The graduate students will also be encouraged to nominate potential visitors through their representative on the Executive Committee. Special attention will be paid to the presence of prominent women and minority scientists in our visitor program. Each Fall a special request will be made to the participating faculty and M. L. Cartwright fellows for suggestions of visitors from under-represented groups. Our experience, from organizing conferences, workshops, and colloquium series, shows that these special requests help generate lists of high-quality scientists.
- **Summer Internships for Minority and Women Undergraduates**.
  Applications and/or nominations for summer internships for promising women and/or minority undergraduates will be sought by advertising and faculty contacts. Qualified students that can be paired with one of the Nonlinear Science Program faculty will be offered support.
- **Traineeship program experimental equipment**.
  The faculty participants responsible for experimental equipment purchased for the IGERT program will make an annual report to the Executive Committee on how the equipment is being used in the graduate training program. Suggestions on how to more efficiently use this equipment within the general graduate training may then be made by the Executive Committee. Any disputes that arise over equipment will be mediated by the directors.
- **Travel funds for conferences**.
  Students may apply for funds to help cover the travel expenses of attending conferences and workshops. Decisions on internship, visitor, equipment and travel fund requests will be made at the quarterly Executive Committee meetings.

I Performance Assessment

The goal of the program is both to train students in nonlinear science and to prepare them for varied scientific and engineering career paths. Thus the definitive evaluation of whether the program has achieved its goals will be based on the career success of the students. In the interim, *detailed* feedback from the students, internship hosts, participating faculty, external advisors, long-term visitors, and thesis advisors is essential since statistical analysis of retention and placement rates would not be reliable for our small sample size. Feedback in the form of written reports will be obtained from the student course evaluations, and also from the minutes of the quarterly Executive Committee meetings and an end-of-year open discussion with the students. The Executive Committee will then prepare a summarizing annual report for NSF that assesses the progress and success of the program.

During the first two years of the IGERT grant the focus will be on evaluating the various individual components of the program with the aim of providing the feedback necessary to modify and improve each aspect of the program. Specifically, we shall assess each of the following components separately.

- **Nonlinear Science Course**. Quantitative indicators of the success of the course are (1) the number of students enrolled, (2) the fraction of the students retained in the second and third quarters, (3) the number of different departments represented by the graduate students and by the faculty, (4) the number of students outside the IGERT Nonlinear Science Program who enroll in the course, (5) the number of faculty actively involved in the course, and (6) the number of projects that lead to publishable results. The most significant qualitative measure of the course's success will be the quality of the group projects and the student reports. The presentation of the project will be critiqued by both students and faculty to assess whether the students have learned to communicate well to a cross-disciplinary group. Other indicators of success are the number of group-projects that lead to longer-term investigations, and new collaborations between faculty and/or students. It is also essential to get student and faculty feedback on how well experimental projects mesh with the theoretical and computational ones.
- **Women in Science Seminar**. The success of this component will be measured by the number of students, postdocs and faculty members that participate regularly. In particular, we are looking for a substantial involvement of women from outside the IGERT program that would indicate impact beyond the Nonlinear Science Program.
- **Nonlinear Science Seminar and Visitor Program**. The seminars and the visitors should provide cutting-edge research relevant to the program participants, and also give the students a broad perspective of nonlinear science. The impact of the seminar series will be assessed through quarterly student questionnaires assessing their interest in the presentations, as well as the extent to which they have provided the students with a general perspective of the field.
- **Regional Workshop**. A measure of success is the attendance and participation in this conference by students, postdocs and senior researchers not only from Northwest-

ern, but also from other universities in the Midwest.

- **Experimental projects**. We will assess whether the experimental equipment, intended for the student experimental projects, is being used to its fullest. A log of equipment use will aid our evaluation, as will the annual report from the faculty in charge of equipment.

After the program has been running for at least two years, it will be possible to examine some additional indicators of the effectiveness of the program:

- **Internships**. The first indicator is the number of students who apply for an internship, as well as the number who submit a report applying for extension of the internship beyond the first 3 months. (Together with the assessment by the host researcher, this report aids us in determining whether the internship is meaningful and should be extended.) Students' final reports, and possibly a publication arising from the work, would provide a basis for assessment of the internship. Towards the end of the program the impact of the internship on the thesis work of the student will be more apparent.
- **Diversity: Mary L. Cartwright Fellowships**. The success of the recipients of the Cartwright fellowship in course work, internships and thesis research will indicate whether the mentoring and recruiting efforts were successful in attracting and keeping top students from under-represented groups. Retention rates will be carefully monitored. The Nonlinear Science Seminar, Visitor Program, and Regional Workshop are additional forums for introducing students to the scientific contributions of minorities and women; our success in attracting participation in these activities from members of under-represented groups will be continually evaluated.
- **Recruitment**. The quality and the acceptance rate of the recruited students will indicate whether the program attracts top students. Specifically, we will compare the credentials of the subset of students recruited to a department with IGERT fellowships with all students recruited to that departmental Ph.D. program.
- **Retention**. An important indicator is the retention rate of students in the program after their first two years, *i.e.*, the number that continue with interdisciplinary thesis research that qualifies for IGERT-fellowships.
- **Ph.D. theses; time-to-degree**. One of the most important indicators will be the number of interdisciplinary Ph.D. thesis projects made possible by the IGERT program. Evaluation of the success of these projects, compared with more traditional Ph.D. theses, will be made. An estimate of the number of thesis projects that lead to new interdisciplinary faculty collaboration within Northwestern and with external researchers will also be made. Time-to-degree will be carefully monitored; the aim is to develop a program that does not increase this number.
- **Publications.** Has the program led to publications that would not have been possible outside the Nonlinear Science Program framework? Does the list of journals where IGERT program publications appear reflect an impact of each Ph.D. thesis on more than one field?

J Recruitment and Retention Experience

The following statistics may underestimate the number of minority students who apply and enroll in the various PhD programs. The Northwestern University Graduate School defines minority students as African-Americans, Alaskan natives, Mexican-Americans, Native Americans and Puerto Ricans.

Table 1: Statistics for Biomedical Engineering Ph.D. program (BME).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	149	55	15	Verbal: 600 Quant.: 760 Anal.: 720	66 full-time	7
Women:	53	20	6	*	25 full-time	3
Minorities:	31	17	0	*	5 full-time	0
1997-8	149	57	10	Verbal: 565 Quant.: 729 Anal.: 674	77 full-time	9
Women:	27	13	5	*	33 full-time	2
Minorities:	5	3	1	*	7 full-time	0
1998-9	91	28	12	Verbal: 610 Quant.: 710 Anal.: 660	69 full-time	10
Women:	29	7	3	*	28 full-time	4
Minorities:	6	2	0	*	5 full-time	1

Average time to degree: 6.3 years

Table 2: Statistics for Chemical Engineering Ph.D. program (ChE).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	266	47	8	Verbal: 560 Quant.: 740 Anal.: 690	54 full-time	8
Women: Minorities:	69 5	13 3	2 1	* *	14 full-time 4 full-time	3 1
1997-8	268	46	11	Verbal: 598 Quant.: 743 Anal.: 707	58 full-time	10
Women: Minorities:	70 2	15 1	3 1	* *	14 full-time 4 full-time	3 1
1998-9	200	53	16	Verbal: 572 Quant.: 745 Anal.: 727	63 full-time	11
Women: Minorities:	59 3	18 3	3 1	* *	14 full-time 4 full-time	5 0

Average time to degree: 4.7 years

Table 3: Statistics for Electrical and Computer Engineering Ph.D. program (ECE).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	560	70	31	Verbal: 540 Quant.: 750 Anal.: 700	138 full-time	21
Women: Minorities:	114 16	26 5	5 1	* *	26 full-time 22 full-time	6 2
1997-8	484	62	36	Verbal: 591 Quant.: 728 Anal.: 677	150 full-time	17
Women: Minorities:	97 12	22 4	7 4	* *	32 full-time 22 full-time	4 2
1998-9	520	53	36	Verbal: 550 Quant.: 770 Anal.: 695	154 full-time	14
Women: Minorities:	104 13	16 5	6 4	* *	30 full-time 21 full-time	3 1

Average time to degree: 5.5 years

Table 4: Statistics for Applied Mathematics Ph.D. program (ESAM).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	37	12	8	Verbal: 550 Quant.: 720 Anal.: 660	36 full-time	5
Women: Minorities:	10 6	1 2	1 1	* *	9 full-time 4 full-time	2 2
1997-8	44	14	9	Verbal: 555 Quant.: 762 Anal.: 718	34 full-time	7
Women: Minorities:	11 0	2 0	1 0	* *	8 full-time 2 full-time	0 0
1998-9	27	12	8	Verbal: 522 Quant.: 751 Anal.: 667	38 full-time	5
Women: Minorities:	7 3	5 2	3 0	* *	11 full-time 2 full-time	3 0

Average time to degree: 4.5 years

Table 5: Statistics for Materials Science and Engineering Ph.D. program (MSE).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	172	51	25	Verbal: 603 Quant.: 751 Anal.: 717	88 full-time	28
Women: Minorities:	49 17	13 5	8 1	* *	23 full-time 5 full-time	9 1
1997-8	243	72	25	Verbal: 560 Quant.: 759 Anal.: 719	77 full-time	23
Women: Minorities:	55 2	17 2	7 1	* *	22 full-time 3 full-time	4 1
1998-9	212	64	26	Verbal: 571 Quant.: 752 Anal.: 710	112 full-time	14
Women: Minorities:	43 2	22 1	7 0	* *	27 full-time 3 full-time	1 0

Average time to degree: 5.5 years

Table 6: Statistics for Mathematics Ph.D. program (Math).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	87	25	10	Verbal: 620 Quant.: 760 Anal.: 700	38 full-time	3
Women: Minorities:	23 6	4 0	2 0	* *	7 full-time 0 full-time	0 0
1997-8	101	31	11	Verbal: 656 Quant.: 752 Anal.: 730	40 full-time	2
Women: Minorities:	39 2	7 0	5 0	* *	9 full-time 0 full-time	0 0
1998-9	104	41	8	Verbal: 685 Quant.: 735 Anal.: 650	38 full-time	7
Women: Minorities:	38 3	13 1	5 1	* *	11 full-time 1 full-time	1 0

Average time to degree: 5.5 years

Table 7: Statistics for Mechanical Engineering Ph.D. program (ME).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	252	84	21	Verbal: 520 Quant.: 750 Anal.: 690	68 full-time	8
Women: Minorities:	31 17	17 6	2 0	* *	5 full-time 4 full-time	0 0
1997-8	163	69	14	Verbal: 610 Quant.: 762 Anal.: 735	84 full-time	17
Women: Minorities:	31 2	9 2	2 2	* *	2 full-time 2 full-time	0 0
1998-9	160	89	18	Verbal: 581 Quant.: 765 Anal.: 701	81 full-time	13
Women: Minorities:	20 1	16 1	5 1	* *	5 full-time 1 full-time	2 0

Average time to degree: 5.1 years

Table 8: Statistics for Physics and Astronomy Ph.D. program (PaA).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	110	47	12	Verbal: 560 Quant.: 770 Anal.: 830	74 full-time	13
Women:	26	9	2	*	13 full-time	3
Minorities:	8	2	0	*	3 full-time	0
1997-8	103	52	16	Verbal: 647 Quant.: 760 Anal.: 753	73 full-time	13
Women:	17	8	4	*	14 full-time	3
Minorities:	3	2	1	*	4 full-time	1
1998-9	89	51	21	Verbal: 564 Quant.: 774 Anal.: 688	76 full-time	10
Women:	12	7	5	*	14 full-time	1
Minorities:	2	1	1	*	4 full-time	0

Average time to degree: 6.7 years

Table 9: Statistics for Institute for Neuroscience Ph.D. program (Phys/NBP).

Year	Applicants	Accepted	Enrolled	Ave. GRE	Students	Ph.D.'s
1996-7	145	39	12	Verbal: 600 Quant.: 693 Anal.: 667	60 full-time	7
Women:	63	19	8	*	30 full-time	3
Minorities:	5	2	0	*	3 full-time	1
1997-8	143	32	14	Verbal: 654 Quant.: 728 Anal.: 731	75 full-time	7
Women:	65	14	7	*	33 full-time	6
Minorities:	1	1	1	*	4 full-time	0
1998-9	143	36	18	Verbal: 624 Quant.: 710 Anal.: 704	81 full-time	13
Women:	62	21	11	*	38 full-time	6
Minorities:	0	0	0	*	4 full-time	0

Average time to degree: 5.0 years

K Recent Training Experience

KEITH BURNS, Department of Mathematics (Math)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 1 graduate student, 0 postdoctoral fellows
- 1997-98: 0 undergraduates, 1 graduate student, 0 postdoctoral fellows
- 1998-99: 0 undergraduate, 1 graduate student, 0 postdoctoral fellows

Courses taught:

- 1996-97:
  Math C03-0: Differential Equations
  Math C30-1: Probability
  Math C29-1: Differential Geometry
  Math E15: Pesin Theory
- 1997-98:
  Math C30-1: Probability
  Math D47-1,2,3: Dynamical Systems
- 1998-99:
  Math C30-1: Probability
  Math D47-1,2,3: Dynamical systems

Other Relevant Educational Activities:

- January 1996-present: Organizer of weekly Dynamical Systems Seminar
- September 1997-present: Freshman advisor
- August 1999 Minicourse on stable ergodicity at AMS Summer Research Institute

PREDRAG CVITANOVIĆ, Department of Physics & Astronomy (PaA)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 3 graduate students, 2 postdoctoral fellows
- 1997-98: 1 undergraduates, 3 graduate students, 1 postdoctoral fellows
- 1998-99: 0 undergraduates, 2 graduate students, 0 postdoctoral fellows

Courses taught:

- 1996-97:

  Physics-D60: Geometry of Chaos

- 1997-98:

  Two lecture course, "Supersymmetry and Trace Formulae: Chaos and Disorder", NATO ASI – Newton Institute, Cambridge, 9–10 sep 97

  Physics D60: Diffusion, transport and non-equilibrium statistical mechanics

  Physics D16-2: Statistical mechanics and modern hydrodynamics

- 1998-99:

  Physics D16-2: Renormalization theory

  Physics D60: Introduction to nonlinear dynamics

  5 lecture course, "Classical and Quantum Trace Formulae", 4th International Summer School/Conference "Let's Face Chaos through Nonlinear Dynamics", Maribor, Slovenia, 27 June - 11 July 1999

Other Relevant Educational Activities:

- 1993–1998: Director, Center for Chaos and Turbulence Studies, Copenhagen.
- 1991–1998: Co-organizer, Niels Bohr Institute – Nordita Institutes Colloquia
- Co-organizer, "Nordic Nonlinear Days 1996", Humlebæk, Denmark, August 24–27, 1996
- Organizer, "Classical and Quantum Chaos", EU Chaos and Quantization network / CATS workshop, Copenhagen, December 12-14, 1996
- January 1997-present: Co-organizer of Northwestern's Interdisciplinary Nonlinear Science Seminar (with H. Riecke and M.Silber)
- Organizer, "Nonlinear Science Festival", CATS 5th year conference, December 7-12, 1998
- December 1996-present: Secretary, "European Nonlinear Days Committee"

STEPHEN H. DAVIS, Department of Engineering Sciences & Applied Mathematics (ESAM)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduate, 5 graduate students, 3 postdoctoral fellows
- 1997-98: 0 undergraduates, 5 graduate students, 4 postdoctoral fellows
- 1998-99: 0 undergraduates, 4 graduate students, 3 postdoctoral fellows

Courses taught:

- 1996-97:
  Math B14-2: Calculus
  ESAM D26: Flows with Small Inertia
  ESAM D27: Flows with Small Viscosity
- 1997-98:
  Math B14-1: Calculus
  ESAM D95: Special Topics in Applied Mathematics - Solidification
- 1998-99:
  Math B14-1: Calculus

JOHN FRANKS, Department of Mathematics (Math)

Student and Postdoctoral Supervision:

- 1996-97: 1 undergraduate, 2 graduate students
- 1997-98: 0 undergraduates, 2 graduate students
- 1998-99: 0 undergraduate, 3 graduate students

Courses taught:

- 1996-97:
  Math B14-1: Calculus
  Math D47-1,2,3: Dynamical Systems
- 1997-98:
  Math B14-3: Calculus
  Math D41-1: Topology of Manifolds
  Math D47-2: Riemannian Geometry
- 1998-99:
  Math B14-3: Calculus
  Math C37-1,2: Modern Algebra
  Math D47-3: Riemannian Geometry

Other Relevant Educational Activities:

- 1996-present: Organize weekly Dynamics seminar
- September 1997-present: Freshman advisor

JAMES C. HOUK, Department of Physiology (Phys)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 3 graduate students, 1 postdoctoral fellows
- 1997-98: 0 undergraduates, 2 graduate students, 4 postdoctoral fellows
- 1998-99: 0 undergraduates, 3 graduate students, 5 postdoctoral fellows

Courses taught in Neurosciences Institute Graduate Program:

- 1996-97:
  D52: Sensorimotor Integration (Co-course Director)
  D20: Neural Systems and Behavior
  D15: The Central Nervous System
- 1997-98:
  D52: Sensorimotor Integration (Co-course Director)
  D20: Neural Systems and Behavior
  D15: The Central Nervous System
- 1998-99:
  D33: Neurobiology of Disease
  D20: Neural Systems and Behavior
  D15: The Central Nervous System

Other Relevant Educational Activities:

- 1997: Organized Panel on "Computational Issues in Motor Learning" for Neural Control of Movement Annual Meeting
- 1996-1999: Organizer of Annual Meeting of NIMH-funded Center of Neuronal Populations and Behavior
- 1999: Contributed lecture session "Cerebro-Cerebellar Pathways, Interactions and the Control of Movement" for Neural Control of Movement Annual Meeting

WILLIAM L. KATH, Department of Engineering Sciences and Applied Mathematics (ESAM)

Student and Postdoctoral Supervision:

- 1996-97: 1 undergraduate, 3 graduate students, 2 postdoctoral fellows
- 1997-98: 0 undergraduate, 3 graduate students, 1 postdoctoral fellow
- 1998-99: 1 undergraduate, 4 graduate students, 1 postdoctoral fellow

Courses taught:

- 1996-97:
  ESAM B52: Honors Calculus for Engineers
  ESAM D30-1,2: Wave Propagation
- 1997-98:
  MEAS EA4: Engineering Analysis 4, Differential Equations
  MATH B14-3: Vector Calculus
  MATH B21: Differential Equations
- 1998-99:
  ESAM D21-1,2,3: Models in Applied Mathematics
  MEAS EA4: Engineering Analysis 4, Differential Equations

Other Relevant Educational Activities:

- Course Design: *Engineering Analysis 4*, a differential equations course incorporating the mathematical theory, applications and programming in MATLAB. Also, a member of the *Engineering First* Committee to redesign the undergraduate engineering curriculum at Northwestern.
- Participant in the Center for Advanced Cement-Based Materials Summer REU (Research Experience for Undergraduates) Program

PREM KUMAR, Department of Electrical and Computer Engineering (ECE)

Student and Postdoctoral Supervision:

- 1996-97: 2 undergraduates, 7 graduate students, 2 postdoctoral fellows
- 1997-98: 2 undergraduates, 10 graduate student, 2 postdoctoral fellows
- 1998-99: 2 undergraduates, 10 graduate students, 3 postdoctoral fellows

Courses taught:

- 1996-97:
  ECE B42: Circuits II
  ECE D06: Nonlinear Optics
  ECE C79: Optics and Information Systems
- 1997-98:
  ECE B42: Circuits II
  ECE D06: Nonlinear Optics
- 1998-99:
  ECE B42: Circuits II
  ECE D06: Nonlinear Optics
  ECE C79: Optics and Information Systems

Other Relevant Educational Activities:

- 1995-present: Instructor for the Short Course "Quantum Properties of Optical Parametric Amplifiers," at various national and international conferences
- January 1991-present: Co-organizer of ECE Department's Colloquia Series in Photonic Systems and Technology

SETH LICHTER, Department of Mechanical Engineering (ME)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 5 graduate students, 0 postdoctoral fellows
- 1997-98: 0 undergraduates, 3 graduate students, 0 postdoctoral fellows
- 1998-99: 0 undergraduates, 2 graduate students, 1 postdoctoral fellow

Courses taught:

- 1996-97:
  ME D25-1: Fundamentals of Fluid Dynamics I
  ME D25-2: Fundamentals of Fluid Dynamics II
  ME B20: Thermodynamics I
- 1997-98:
  ME D25-2 Fundamentals of Fluid Dynamics II
  ME D29 Turbulent Flows
  ME B05-3 Engineering Analysis III
- 1998-99:
  ME D25-2 Fundamentals of Fluid Dynamics II
  ME B05-3 Engineering Analysis III (two sections)

Other Relevant Educational Activities:

- 1994-96: Steering Committee member for the Midwest Universities Fluid Mechanics Retreat
- January 1994-present: Coordinator at Northwestern University for the Midwest Mechanics Seminar Tour
- Summer 1996: NSF Research Experience for Undergraduates (REU), 1 student
- 1996-present: Member of Northwestern University's Undergraduate Study Abroad Committee
- 1998: Faculty Advisor for Northwestern University's Tech Design Competition

BERNARD J. MATKOWSKY, Department of Engineering Sciences & Applied Mathematics (ESAM), Department of Mathematics (Math), Department of Mechanical Engineering (ME)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 4 graduate students, 4 postdoctoral fellows
- 1997-98: 0 undergraduates, 3 graduate students, 4 postdoctoral fellows
- 1998-99: 0 undergraduates, 4 graduate students, 4 postdoctoral fellows

Courses taught:

- 1996-98:
  Math B21: Introduction to Differential Equations
- 1998-99:
  Math B13: Review of Calculus of One Variable

Other Relevant Educational Activities:

- Department Chairman (ESAM)
- Chairman of Colloquium Committee (ESAM)
- Organizer of Combustion Seminar

FERDINANDO A. MUSSA-IVALDI, Department of Physiology

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 10 graduate students, 3 postdoctoral fellows
- 1997-98: 0 undergraduates, 2 graduate students, 2 postdoctoral fellows
- 1998-99: 0 undergraduates, 2 graduate students, 4 postdoctoral fellows

Courses taught:

- 1997-98:

  Neuroscience D45: Principles of Learning

Other Relevant Educational Activities:

- September 1994-present: Organizer of weekly meeting of the Motor Learning and Biorobotics group
- April 1999: Tutor in a problem-based learning course for medical students

<u>JULIO M. OTTINO</u>, Department of Chemical Engineering

<u>Student and Postdoctoral Supervision</u>:

- 1996-97: 0 undergraduates, 5 graduate students, 2 postdoctoral fellows
- 1997-98: 2 undergraduates, 6 graduate students, 2 postdoctoral fellows
- 1998-99: 3 undergraduates, 5 graduate students, 1 postdoctoral fellows

<u>Courses taught</u>:

- 1996-97:
  CES 710-D89 Selected Topics - Problem Solving and Creativity
- 1997-98:
  CES 710-D89 Selected Topics - Problem Solving and Creativity

<u>Other Relevant Educational Activities</u>:

- September 1991-present: Chair of Department of Chemical Engineering

HERMANN RIECKE, Department of Engineering Sciences & Applied Mathematics (ESAM)

Student and Postdoctoral Supervision:

- 1996-1997: 0 undergraduates, 2 graduate students, 0 postdoctoral fellows
- 1997-1998: 0 undergraduates, 2 graduate students, 0 postdoctoral fellows
- 1998-1999: 0 undergraduates, 4 graduate students, 1 postdoctoral fellow

Courses taught:

- 1996-1997:
  ESAM C-21-1,2: Models in Applied Mathematics-1,2 (2 quarters)
  ESAM D-46-1,2: Numerical Methods for Partial Differential Equations-1,2 (2 quarters)
- 1997-1998:
  MATH B-14-1: Calculus-1
  ESAM D-21-1,2,3: Models in Appl. Math.-1,2,3 (3 quarters)
- 1998-1999:
  ENGG B-05-4: Engineering Analysis IV - Differential Equations
  ESAM C-11-3: Complex Variables
  MATH B-14-3: Calculus-3, 2 sections

Other Relevant Educational Activities:

- 1996-present: Organize weekly Pattern Formation Journal Club (with M. Silber)
- January 1997-present: Co-organizer of Northwestern's Interdisciplinary Nonlinear Science Seminar
- October 1997: Co-organizer of 1^{st} Northwestern University/University of Chicago Joint Workshop on Nonlinear and Complex Systems
- October 1998: Co-organizer of 3^{rd} Northwestern University/University of Chicago Joint Workshop on Nonlinear and Complex Systems
- July 1996: Mini-Course on *Binary-Fluid Convection* at the Summer Institute for Geophysical Fluid Dynamics of the Woodshole Oceanographic Institute, 8 lectures (jointly with P. Kolodner, Bell Laboratories, Lucent Technologies)
- September 1998: 3 Lectures at Summer School *Waves, Vortices, Dunes: Structures in Laboratory and Nature* of the Heraeus Foundation, University of Magdeburg, Germany

MARY SILBER, Department of Engineering Sciences & Applied Mathematics (ESAM)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 2 graduate students, 0 postdoctoral fellows
- 1997-98: 1 undergraduate, 2 graduate students, 0 postdoctoral fellows
- 1998-99: 1 undergraduate, 3 graduate students, 0 postdoctoral fellows

Courses taught:

- 1996-97:
  ESAM B52-2,3: Honors Calculus for Engineers-2,3
  ESAM C22: Applied Dynamical Systems
- 1997-98:
  Math B13: Review of Calculus of One Variable (2 sections)
  ESAM C11-3: Complex Variables
  ESAM D12-3: Methods of Nonlinear Analysis-3
- 1998-99:
  Math B13: Review of Calculus of One Variable
  ESAM B52-1,2: Honors Calculus for Engineers-1,2

Other Relevant Educational Activities:

- January 1994-present: Co-organizer of weekly Pattern Formation Journal Club (with H. Riecke)
- January 1997-present: Co-organizer of Northwestern's Interdisciplinary Nonlinear Science Seminar (with P. Cvitanović and H. Riecke)
- October & May 1997, 1998, 1999: Organizing Committee for the Northwestern University/University of Chicago Joint Workshop on Nonlinear and Complex Systems
- 1997-1998: Consultant for the Mathematical Association of America's Project NExT (New Experiences in Teaching)

SARA A. SOLLA, Department of Physiology (NUMS)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 3 graduate students, 0 postdoctoral fellows
- 1997-98: 1 undergraduate, 3 graduate students, 0 postdoctoral fellows
- 1998-99: 0 undergraduate, 4 graduate students, 0 postdoctoral fellows

Courses taught:

- 1997-98:

  Introduction to Neural Computation (Graduate course)
- 1998-99:

  Theories of Unsupervised Learning (Graduate reading course)

Other Relevant Educational Activities:

- Tutorial on "The Dynamics of On-Line Learning", 1996 International Conference on Artificial Neural Networks, Bochum, Germany, July 16, 1996
- Three lecture course on "Statistical Mechanics Theory of Learning and Generalization", Cargese Summer School on Neural Information Processing, Cargese, France, July 7–12, 1997
- Five lecture course on "Models for Learning and Adaptation", NORDITA Masterclass in Physics, Copenhagen, Denmark, July 26–August 2, 1997
- Five lecture course on "Neural networks for Bayesian inference", School on Neural Information Processing, Trieste, Italy, May 3–7, 1999

<u>NELSON SPRUSTON</u>, Department of Neurobiology & Physiology (NBP)

<u>Student and Postdoctoral Supervision</u>:

- 1996-97: 1 undergraduates, 1 graduate student, 1 postdoctoral fellows
- 1997-98: 2 undergraduates, 2 graduate students, 3 postdoctoral fellows
- 1998-99: 1 undergraduates, 1 graduate students, 1 postdoctoral fellows

<u>Courses taught</u>:

- 1996-97:
  Biology C02: Fundamentals of Neuroscience
  Neuroscience D60: Excitable Membranes
- 1997-98:
  Biology C02: Fundamentals of Neuroscience
  Neuroscience D10: Excitable Membranes
  Neuroscience D60: Dendritic Excitability
- 1998-99:
  Neuroscience D10: Excitable Membranes

<u>Other Relevant Educational Activities</u>:

- 1999-present: Chair, Curriculum Committee, Northwestern University Institute for Neuroscience

MELODY SWARTZ, Department of Biomedical Engineering (BME), Department of Chemical Engineering (ChE)

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 0 graduate student, 0 postdoctoral fellows
- 1997-98: 0 undergraduates, 0 graduate students, 0 postdoctoral fellows
- 1998-99: 0 undergraduates, 0 graduate students, 0 postdoctoral fellows

Courses taught:

- 1998-99:

  Transport and Mechanics in Living Systems, Tufts University, Department of Chemical Engineering

PAUL B. UMBANHOWAR, Department of Physics & Astronomy (WCAS)

Student and Postdoctoral Supervision:

- 1996-97: 2 undergraduates, 0 graduate students, 0 postdoctoral fellows
- 1997-98: 0 undergraduates, 2 graduate students, 0 postdoctoral fellows
- 1998-99: 5 undergraduates, 2 graduate students, 0 postdoctoral fellows

Courses taught:

- 1998-99: WCAS C39-2: Quantum Mechanics

PETER W. VOORHEES, Department of Materials Science and Engineering

Student and Postdoctoral Supervision:

- 1996-97: 1 undergraduates, 5 graduate students, 2 postdoctoral fellows
- 1997-98: 2 undergraduates, 5 graduate students, 2 postdoctoral fellows
- 1998-99: 5 undergraduates, 4 graduate students, 2 postdoctoral fellows

Courses taught:

- 1996-97:
  MSE D07: Phase Transformations in Materials
  MSE C96: Senior Thesis
  MSE D11: Phase Transformations in Crystalline Materials
- 1997-98:
  MSE C22: Kinetics of Heterogeneous Reactions
  MSE D01: Chemical Thermodynamics
- 1998-99:
  MSE C16-1: Microstructural Dynamics
  MSE D01: Chemical Thermodynamics

Other Relevant Educational Activities:

- 1998-1999: Head of Graduate Admission for Department of Materials Science and Engineering

AMIE WILKINSON, Department of Mathematics

Student and Postdoctoral Supervision:

- 1996-97: 0 undergraduates, 0 graduate students, 0 postdoctoral fellows
- 1997-98: 0 undergraduates, 0 graduate students, 0 postdoctoral fellows
- 1998-99: 0 undergraduates, 1 graduate student, 0 postdoctoral fellows

Courses taught:

- 1996-97:

  Math B92-1-2-3: Accelerated Mathematics for Mathematical Methods in the Social Sciences: First Year

  Math C13-1-2: Chaotic Dynamical Systems

- 1997-98:

  Math B92-1-2-3: Accelerated Mathematics for Mathematical Methods in the Social Sciences: First Year

  Math C13-1: Chaotic Dynamical Systems

  Math D12: Graduate Topics Course (Harmonic Measures and Foliations)

- 1998-99:

  No teaching (on NSF Graduate Research Fellowship)

Other Relevant Educational Activities:

- 1996-1997: Organized (with K. Burns and J. Franks) weekly graduate research seminar in ergodic theory

L Students and Collaborators

<u>**KEITH BURNS**</u>, Department of Mathematics

- **Ph.D. Thesis Advisor**:
  Anthony Manning
- **Postdoctoral Advisors**:
  M. Brin
- **Graduate Students**:
  completed Ph.D.: Kurt Cogswell, Jason Holt
- **Other co-authors and collaborators (past 4 years)**:
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- **Ph.D. Thesis Advisor**:

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- **Postdoctoral Advisors**:

  S. Adler, S. Drell, B. Lautrup J.C. Taylor,

- **Graduate Students**:

  completed Ph.D.: R. Artuso, E. Aurell, F. Christiansen, G. Gunaratne (main advisor M.J. Feigenbaum), K. Hansen, M.H. Jensen (main advisor P. Bak), V. Putkaradze (main advisor T. Bohr), H.H. Rugh, P.E. Rosenqvist, G. Russberg, T. Schreiber (main advisor P. Grassberger)
  completed M.Sci.: E. Gyldenkerne, Sune F. Nielsen
  current Ph.D.: N. Søndergaard, V. Moroz

- **Postdoctoral Fellows**:

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- **Other co-authors and collaborators (past 4 years)**:

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STEPHEN H. DAVIS, Department of Engineering Sciences & Applied Mathematics (ESAM)

- **Ph.D. Thesis Advisor**:

  L. Segel

- **Graduate Students**:

  V.S. Ajaev, D.M. Anderson, M.A. Boudourides, K. Brattkus, R.J. Braun, R.H. Buckholz, J.P. Burelbach, J.B. Culkin, J.A. Dantzig, D.J. Diller, J.J. Dudis, E.B. Dussan, R.P. Flemming, J.B. Grotberg, I.H. Herron, D.A. Huntley, C.H.G. von Kerczek, D. Kirill, A.K. Liu, P.Q. Luo, G.J. Merchant, G.P. Neitzel, C.H. Panzarella, B. Reisfeld, M.N. Roppo, W.W. Schultz, T.P. Schulze, M.K. Smith, B.J. Spencer, P.H. Steen, B.S. Tilley, M.B. Williams, G.W. Young

- **Postdoctoral Fellows**:

  L. Bühler, D.J. Canright, Y.J. Chen, S.J. Cowley, P. Ehrhard, A.A. Golovin, H.P. Grimm, L.W. Horn, R. Hoyle, S.W. Joo, C.H.G. von Kerczek, I. Kliakhandler, S. Linz, P. Metzner, A. Oron, A.K. Sen, M.J. Tan, A. Umantsev, S.K. Wilson, H. Wong, J.J. Xu

- **Other co-authors and collaborators**:

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JOHN FRANKS, Mathematics Department (Math)

- **Ph.D. Thesis Advisor**:

  Steven Smale

- **Graduate Students**:

  J. Alongi, S. Asher, S. Batterson, J. Bauer, E. Doeff, G. Frank, S. Hetzler, R. Holmgren, C. Jacobson, A. Madden, C. Narasimhan, K. deRezende, D. Richeson, E. Rykken, M. Snavely, M. Stafford

- **Co-authors and other collaborators (past 4 years)**:

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__**JAMES C. HOUK**__, Department of Physiology (Phys)

- **Mentors**:

  Elwood Henneman, M.D., Yves Laporte, M.D., Lawrence Stark, M.D.

- **Graduate Students**:

  L. Eisenman, D. Fraser, A. Gruber, L. He, S. Hua, S. Mahamud, C. Mason, J. Nocher, K. Novak

- **Postdoctoral Fellows**:

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- **Co-authors and other collaborators (past 4 years)**:

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<u>**WILLIAM L. KATH**</u>, Department of Engineering Sciences & Applied Mathematics (ESAM)

- **Ph.D. Thesis Advisor**:

  Donald S. Cohen

- **Postdoctoral Advisors**:

  Donald S. Cohen

- **Graduate Students**:

  Completed Ph.D.: C.V. Hile, A. Kahlow Hobbs, J.N. Kutz, M.J. Mills D.J. Muraki, A.M. Niculae, T. Ueda
  Current Ph.D.: B. Marks, R. Moore, L. Hernandez-Reyna, S. Bhatt

- **Postdoctoral Fellows**:

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- **Other co-authors and collaborators (past 4 years)**:

  A. Agarwal, J.C. Alexander, G. Bartolini, S.G. Evangelides M. Fedoruk, C.K.R.T. Jones, A.D. Kim, P. Kumar, R.D. Li, D. Marcuse, A. Mecozzi, C. Menyuk, A.V. Sahakian, B. Sanstede, D.K. Serkland, N.F. Smyth, S. Turitsyn, A. Wai, J.W. Zhang

PREM KUMAR, Department of Electrical and Computer Engineering (ECE)

- **Ph.D. Thesis Advisor**:

  Gilbert O. Brink

- **Postdoctoral Advisors**:

  J.-C. Diels, M. M. Salour, J. H. Shapiro

- **Graduate Students**:

  completed Ph.D.: Orhan B. Aytür, Glenn D. Bartolini, David O. Caplan, Sang-Kyung Choi, Jianming Huang, Chonghoon Kim, Dmitry Levandovsky, B. Matthew Poelker, Michael Vasilyev
  completed M.S.: Anjali Agarwal, Sina Balkir, Franco Chiappori, David R. Gerwe, Dave Hochfelder, Joe Hoke, Gregory Kanter, Alex Kaz, Esther Kerbis, Jerry LaChapelle, Robert H. Nakata
  current Ph.D.: Anjali Agarwal, Greg Kanter, Chris Lowrie, Jay Sharping, Yikai Su, Brian Taylor, Paul Voss, Zhilin Wu

- **Postdoctoral Fellows**:

  current: Tae-Gon Noh, Lijun Wang
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- **Other co-authors and collaborators (past 4 years)**:

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SETH LICHTER, Department of Mechanical Engineering (ME)

- **Ph.D. Thesis Advisor**:

  Ascher H. Shapiro

- **Graduate Students**:

  completed Ph.D.: Oliver V. Atassi, Hassan Ayanle, Jyh-Min Chen, Minsub Han, Loong-Piu Kwok, Chih-Yu Lin, Yeong-Yan Perng, William B. Underhill
  completed M.Sci.: Joseph Bull, Brian P. Conlon, Harald J. H. M. van Dongen, Alexander Jung, Daniel Warkentin
  current Ph.D.: Meihong Sun

- **Postdoctoral Fellows**:

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- **Other co-authors and collaborators (past 4 years)**:

  Andrew J. Bernoff, Tony C. F. Chen , Christopher G. Goedde, Mark M. Weislogel

BERNARD J. MATKOWSKY, Department of Engineering Sciences & Applied Mathematics (ESAM), Department of Mathematics (Math), Department of Mechanical Engineering (ME)

- **Ph.D. Thesis Advisor**:

  Joseph B. Keller

- **Graduate Students**:

  completed Ph.D.: A. Class, M. Klosek-Dygas, C. Knessl, R.A. Kuske, T.K.E. Ma, D.O. Olagunju, L. Putnick, C. Raymond, D.A. Schult, D. Stevens
  current Ph.D.: J. Park, C. Wahle

- **Postdoctoral Fellows**:

  A.P. Aldushin, M.R. Booty, A. Class T. Erneux, M. Garbey, J. Grasman, A. van Harten, T.J. Mahar, S.B. Margolis, E. Nekrasov, E.N. Rumanov, G.V. Shkadinskaya, K.G. Shkadinsky, G.I. Sivashinsky, J.M. Vega, Vl. Volpert

- **Co-authors (past four years)**:

  A.P. Aldushin, A. Bayliss, A. Class, T.K.E. Ma, D.A. Schult, G.V. Shkadinskaya, K.G. Shkadinsky, Vl. Volpert

FERDINANDO A. MUSSA-IVALDI, Department of Physiology

- **Ph.D. Thesis Advisor**:

  P. Morasso

- **Postdoctoral Advisors**:

  E. Bizzi, N. Hogan

- **Graduate Students**:

  completed Ph.D.: M. Conditt, E. Fasse (main advisor N. Hogan), F. Gandolfo (main advisor E. Bizzi), A. Hodgson (main Advisor N. Hogan), E. Loeb (main advisor E. Bizzi), J. Mansfield (main advisor N. Hogan), J. McIntyre (main advisor E. Bizzi), K. Mosier (main advisor T. Gay), D. Rancourt (main advisor N. Hogan), D. Russel (main Advisor N. Hogan), R. Scheidt (main advisor W.Z. Rymer)
  current Ph.D.: C. Lee, B. Reger (co-advisor J.E. Colgate)
  current graduate students supervised during lab rotations: C. Laredo, K. Messing, M. Nataraja, R. Theiss

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<u>**JULIO M. OTTINO**</u>, Department of Chemical Engineering

- **Ph.D. Thesis Advisors**:

  C.W. Macosko, W.E. Ranz

- **Graduate Students**:

  completed Ph.D.: L. Bresler, V. Chakravarthy, R. Chella, M. Chippalkati, T.J. Danielson, S.D. Fields, J.G. Franjione, S. Hansen, D.V. Khakhar, H.A. Kush, C.K. Leong, J.J. McCarthy, F.J. Muzzio, T. Niederkorn, H. Rising, S. Jana, J.E. Sax, M. Serrano, E.M. Sevick, N. Shah, P. Swanson, M. Tjahjadi
  current Ph.D.: J. Fountain, J. Gilchrist, M. Horner, N. Jain, K. Smith

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HERMANN RIECKE, Department of Engineering Sciences & Applied Mathematics (ESAM)

- **Ph.D. Thesis Advisor**:

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- **Postdoctoral Advisor**:

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- **Graduate Students**:

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MARY SILBER, Department of Engineering Sciences & Applied Mathematics (ESAM)

- **Ph.D. Thesis Advisor**:

  Edgar Knobloch

- **Postdoctoral Advisors**:

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SARA A. SOLLA, Department of Physiology (NUMS)

- **Ph.D. Thesis Advisor**:

  Eberhard K. Riedel

- **Postdoctoral Advisors**:

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M Existing Facilities and Equipment

In this section we focus on the infrastructure that Northwestern University will commit to the IGERT Nonlinear Science Program. As this is a training program that requires no large equipment, but considerable training resources, we include here also the Northwestern University commitments to recruiting and support for the Nonlinear Science Program.

The IGERT **Nonlinear Science Program office** and the **common meeting room** will be housed in the same building as the participating engineering, applied mathematics, and physics departments. The building already has fully operational **local area network**, **video-teleconferencing** classrooms, **stockrooms**, **machine shop**, **electronics shop**, as well as a **graduate student machine shop**.

Except for the laboratories in the Northwestern University Medical School (Chicago campus) the participating faculty laboratories are all housed in the same building, the Technological Institute. **Laboratory infrastructure** is already in place in the labs of the experimentalists (Houk, Umbanhowar, Kumar, Lichter, Ottino). The labs will be made accessible to the students engaged in specific experimental projects. In cooperation with the participating departments an effort will be made to provide for **shared office space** for the Nonlinear Science Program graduate students.

Northwestern University has a long history of encouraging cross-departmental and interdisciplinary research. The **Nonlinear Science Institute** at Northwestern University, which will begin operation in Fall 2000, pending support through an NSF IGERT grant, aims at furthering such an environment. The proposed IGERT program would play a central role, spanning the Weinberg College of Arts and Sciences, the McCormick School of Engineering and Applied Science, and the Northwestern University Medical School. As detailed in the supporting letter by Vice President for Research (appended to budget justification), the Deans of the three participating Schools and the University strongly support the initiative.

The University and school administrations will fund the program for an initial three–year period at the level of $150K over 3 years, which will provide for

- budget for the Nonlinear Science seminar series and incidental operational expenses,
- part–time administrative/technical support
- office equipment including networked computer, printer, photocopier, fax, phone.

The success of the IGERT program will depend on Northwestern University's graduate training resources. Northwestern University already has strong faculty in nonlinear sciences, and its commitment to strengthening the research effort in this field is demonstrated by recent senior **faculty appointments** in physics (Cvitanović), in physiology (Solla), and assistant professor appointments in physics (Umbanhowar) and mathematics (Wilkinson). Further faculty searches within fields that would strengthen the IGERT program are planned.