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PI/PD Name: David H Laidlaw

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

Check here if you do not wish to provide any or all of the above information (excluding PI/PD name): ☐

REQUIRED: Check here if you are currently serving (or have previously served) as a PI, co-PI or PD on any federally funded project ☒

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PI/PD Name: George E Karniadakis

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☐ Not Hispanic or Latino

Race:
(Select one or more)

☐ American Indian or Alaska Native
☐ Asian
☐ Black or African American
☐ Native Hawaiian or Other Pacific Islander
☒ White

Disability Status:
(Select one or more)

☐ Hearing Impairment
☐ Visual Impairment
☐ Mobility/Orthopedic Impairment
☐ Other
☒ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

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PI/PD Name: Peter D Richardson

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☐ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)
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- ☐ Visual Impairment
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- ☐ Other
- ☒ None

Citizenship: (Choose one) ☐ U.S. Citizen ☒ Permanent Resident ☐ Other non-U.S. Citizen

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PI/PD Name: Sharon M Swartz

Gender: ☐ Male ☒ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race:
(Select one or more)
☐ American Indian or Alaska Native
☐ Asian
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Disability Status:
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List of Suggested Reviewers or Reviewers Not To Include (optional)

SUGGESTED REVIEWERS:
Not Listed

REVIEWERS NOT TO INCLUDE:
Not Listed

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 04-2 NSF 04-012 02/24/04	FOR NSF USE ONLY NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) CCF - ITR FOR NATIONAL PRIORITIES (continued)	

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
				001785542	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY?
050258809	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE Brown University	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE Brown University 164 Angell Street Providence, RI. 02912
AWARDEE ORGANIZATION CODE (IF KNOWN) 0034017000	
NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE	ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE
PERFORMING ORGANIZATION CODE (IF KNOWN)	

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS
☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **ITR-\(ASE\)-\(sim+dmc+int\) Computational simulation, modeling, and visualization for understanding unsteady bioflows**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 3,980,764	60 months	09/01/04	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
- ☐ BEGINNING INVESTIGATOR (GPG I.A)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.B, II.C.1.d)
- ☐ HISTORIC PLACES (GPG II.C.2.j)
- ☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
- ☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date ________
- ☐ HUMAN SUBJECTS (GPG II.D.6) Exemption Subsection ________ or IRB App. Date ________
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j) ________
- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.E.1)

PI/PD DEPARTMENT Computer Science Department	PI/PD POSTAL ADDRESS Box 1910 Providence, RI 02912 United States
PI/PD FAX NUMBER 401-863-7657	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME David H Laidlaw	PhD	1995	401-863-7647	dhl@cs.brown.edu
CO-PI/PD George E Karniadakis	PhD	1987	401-863-1217	gk@cfm.brown.edu
CO-PI/PD Peter D Richardson	D.Sc.	1974	401-863-2687	Peter_Richardson@Brown.edu
CO-PI/PD Sharon M Swartz	Ph.D.	1988	401-863-1582	sharon_swartz@brown.edu
CO-PI/PD				

CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 04-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Appendix C of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Appendix D of the Grant Proposal Guide.

Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME		

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) - continued from page 1
(Indicate the most specific unit known, i.e. program, division, etc.)

CNS - ITR FOR NATIONAL PRIORITIES
EF - ITR FOR NATIONAL PRIORITIES

Project Summary

Understanding Unsteady Bioflows through Simulation, Modeling, Visualization, Art, and Psychology

David H. Laidlaw (PI)
Computer Scientist
George E. Karniadakis (Co-PI)
Applied Mathematician

Sharon Swartz (Co-PI)
Evolutionary Biologist
Peter D. Richardson (Co-PI), Bioengineer
Kenneth Breuer, Fluid Dynamicist

George Lauder (Co-PI)
Biologist
Harvard

Michael J. Tarr
William H. Warren
Perceptual Psychologists

Fritz Drury
Artist
Rhode Island School of Design

We propose a multi-disciplinary research project to discover new distributed simulation, visualization, and analysis tools for interacting with and understanding multi-valued volumes of scientific data and the biological phenomena they measure. The tools will be developed and evaluated in close collaboration with biologists studying three independent flow-related problems: coronary artery lesion and thrombus formation, the mechanisms and evolution of bat flight, and the mechanism and evolution of fish propulsion and maneuvering.

Intellectual Merit.

The proposed work addresses the National Priority Area of Advanced Science and Engineering (ASE) and several of the technical focus areas. It enables new forms of scientific research by developing new simulation capabilities (sim), integrating distributed experimental and simulation data (dmc+sim), and creating new human-computer interaction and visualization techniques for leveraging human intelligence (int).

The intellectual merit of the work includes advancing basic scientific understanding in the three biological application areas. In addition, the experimental methodology of acquiring 3D motion and flow data using 3D Digital Particle Image Velocimetry (DPIV) and high-speed video will advance the state of the art for studying flow interactions with other biological and man-made systems and may be used for prediction, risk-assessment and decision-making.

As we address these driving biological areas, we expect to discover solutions to some of the current hard problems in scientific visualization, including visualization of multi-dimensional time-varying multi-valued data, visualization of uncertainty, evaluation of the efficacy of visualization methods, and synthesis of visualization and computational modeling methods that are broadly applicable.

We will work to model expert visual designer knowledge, incorporating it into the quantitative evaluation process and building a system for automatically optimizing visualization methods based on such knowledge. We will also compare the effectiveness of visualization applications in several computing and displaying environments including a 4-wall Cave, a stereo display operating at the limit of human acuity, a 40'x40' virtual environment with a head mounted display, stereo-enabled desktop workstations with and without head-tracking, and standard desktop workstations. These characterizations will advance our knowledge about the kinds of interface hardware, user interface techniques, and visualization methods that will most effectively advance science and support reliable complex distributed systems.

The simulation and modeling work to address the biological problems will create new simulation methods for coupling unsteady flow and structure calculations, new methods for incorporating uncertainty into unsteady simulation results, new methods for combining unsteady experimental and simulation data to facilitate comparisons between them, and new methods for filling in gaps in unsteady experimental data.

Broader Impact.

Results from addressing these hard visualization problems for biological fluid flow applications are likely to generalize to other fluid applications, such as weather modeling and defense-related fluid simulations, as well as to other types of scientific data, such as medical imaging data. They have the potential to advance the pace of science and engineering (ASE) in many disciplines. These results may also apply beyond scientific applications by suggesting ways that visualization hardware and software can be most effectively used in many kinds of human-computer interaction.

Advances in the understanding of arterial flow have the potential to ultimately save lives and improve the quality of life for a significant portion of the population. An understanding of bat flight and fish propulsion mechanisms and evolution may go beyond the clear biological significance and direct us to more efficient and functional flying, floating, or submersible vehicles.

The collaborative aspects of this project may be useful quite broadly. Insight into collaborative research are could help make it more common. This work tightly integrates education and research. Students in all disciplines, including biologists, engineers, computer scientists, artists, designers, and perceptual psychologists will advance this interdisciplinary agenda as they develop their own careers, building a more diverse IT workforce.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Project Description

Understanding Unsteady Bioflows through Simulation, Modeling, Visualization, Art, and Psychology

David H. Laidlaw (PI)
Computer Scientist

Sharon Swartz (Co-PI)
Evolutionary Biologist

George Lauder (Co-PI)
Biologist
Harvard

George E. Karniadakis (Co-PI)
Applied Mathematician

Peter D. Richardson (Co-PI), Bioengineer
Kenneth Breuer, Fluid Dynamicist

Michael J. Tarr
William H. Warren
Perceptual Psychologists

Fritz Drury
Artist
Rhode Island School of Design

The purpose of computing is insight, not numbers – Hamming

We propose to develop and evaluate computational modeling, simulation, visualization, and data-analysis tools and apply them to specific scientific areas involving time-varying flows near complex 3D boundary shapes. Tools will be developed in a highly multi-disciplinary manner, incorporating insights and knowledge from the biological domains, engineering, applied mathematics, computer science, visual design, art education, and perceptual psychology.

The research process will integrate all the disciplines through the following steps. Biologists will pose hypotheses about how the biological systems they study interact with fluids. Together with engineers, they will capture relevant 3D motion of the biological systems as well as 3D time-varying flow measurements from around the systems. Applied mathematicians will simulate 3D time-varying flows consistent with the captured motion. They will also create computational models of both the motion and the unsteady flows. Biologists will then work with computer scientists to use new visualization software to visualize the resulting complex motion and flow data to evaluate the original scientific hypotheses. These visualizations will be of the captured data, the simulated data, and computational models merging the two. The new visualization software will be developed with expert input from artists, designers, and perceptual psychologists.

Computational modeling research will include both direct numerical simulation and modal analysis (proper orthogonal decomposition) to create parameterized flow solutions in which the parameters allow 'what if' questions to be posed interactively. With these and other parameterized solutions, we will be able to interpolate across relatively large gaps in experimental data, allowing more effective comparison with simulated results and permitting more thorough and effective 3D visual analysis.

Simulation research will include developing methods for computing flows and flow-structure interactions as well as for propagating uncertainty through the simulation process. Without knowledge of uncertainty, we cannot know whether features we see are significant. Simulated uncertainty will also propagate to and be visualized in our visualization research.

Visualization research is at a crossroad. There are many visualization methods that address relatively simple problems well, but complicated data that is time-varying, 3D, multi-valued, and uncertain are very difficult to explore with these tools. In a sense, today's methods comprise a set of visualization primitives. How to choose the right primitives, combine them effectively, identify and discover primitives that are missing, and then select the right colors, line weights, transfer functions, or other parameters for each primitive is a tremendous challenge. Mechanisms exist for building hybrid visualizations, but not for guiding users to effective ones. A solution would enable many areas of science and engineering to advance more quickly.

Interactive visualization tools will be developed for immersive virtual-reality display devices, including an existing Cave (developed with the help of an NSF Major Research Instrumentation (MRI) grant) and a desktop system with resolution at the limit of human acuity. We will develop these methods in our research group and in a novel interdisciplinary class of both visual design students and computer science students; the students will use new visualization prototyping tools that help leverage visual-design knowledge in this unfamiliar interactive 3D medium. A novel evaluation framework for 3D flow visualization methods will be created and applied to compare the efficacy of existing and proposed visualization methods. This framework will combine approaches from perceptual psychology, art history, and art education to characterize the strengths and weaknesses of visualization methods. As the evaluation system is used, it will capture design knowledge about effective visualizations, and we will mine that knowledge to create a system for improving visualization methods automatically. Artists will participate not only in synthesizing new visualization methods but also in critically evaluating such methods, using an approach that we have found can compete with the kinds of quantitative studies perceptual psychologists use. Perceptual psychologists have been developing experiments for understanding perception for decades, and they will help develop methodology and expertise for evaluating visualization methods in close collaboration with biologists, fluids researchers, engineers, mathematicians, artists, and computer scientists.

While our focus is on the development of computational tools, they will be designed with three driving scientific applications as a guide and test of their efficacy. Without a real application, computational tools often do not address real needs. First, blood flow in moving, deforming cardiac artery models will be studied to better understand atherosclerotic lesion formation and platelet-dominated thrombosis. Second, the movement of fish fins and their interactions with fluid will be studied to better understand fish propulsion and maneuvering. Third, bat flight will be studied to better understand its mechanics and the interplay between flight abilities and species evolution. We will use experimentally-acquired 3D kinematic data acquired via high-speed video and 3D flow data acquired via digital particle image velocimetry (DPIV), as well as simulated flow around models built from the captured motion. The DPIV system was developed with support from an NSF MRI grant. The captured motion data, the experimental flow data, and the simulated flow data will all be complementary, each helping to validate results derived from the others.

Why Biological Fluid Flow? Fluid flows are ubiquitous features of our world, dictating the nature of such diverse phenomena as respiration, flight, and geological processes, at scales from molecular to galactic. While fluid flows are well understood in some regimes, there are many in which they are not, especially when using "flat" visualization techniques. The pervasive presence of fluid flows and fluid-solid interactions in scientific problems at all scales makes them an excellent target for visualization research – solutions to problems will be significant in multiple disciplines. In earlier NSF-funded work, we studied a broader set of scientific application areas, including remote sensing and medical imaging. One of our findings was that biological fluid flow visualizations require solutions to most of the most challenging problems in visualization and computational modeling of any kind of data. These problems include visualizing multi-dimensional time-varying multi-valued data, visualizing uncertainty, evaluating the efficacy of visualization methods, and creating visualization and computational modeling methods that are broadly applicable. Results from addressing these problems for biological fluid flow applications can generalize both to other fluid applications such as weather modeling and defense-related flow simulations as well as to other types of data such as those from medical imaging or structural mechanics.

Cross-disciplinary Connections. The proposed work is unusually interdisciplinary. As with most successful interdisciplinary work, participants from each discipline not only contribute to the work but also benefit from the collaboration, creating a whole that is more than the sum of the parts.

There are many parts of the proposed work that will leverage input from multiple disciplines. Biologists will seek input from the visualization and simulation scientists to understand how various scientific hypotheses can be tested. Visualization experts will need insight from fluid dynamicists, simulation scientists, and biologists about flow features that are important to portray both from a physics perspective and from a biological perspective. Artists and designers will be involved with computer scientists both in synthesizing visualization and in critically evaluating or scoring them. And perceptual psychologists will participate in the evaluation process by helping design experiments and define a perceptually coherent model for interpolating scores. All of the disciplines will be represented as we teach students in the proposed scientific visualization class about biology, flow, and design.

1 Relevance to ITR, NSF, and National Priorities

Our interdisciplinary effort addresses the national priority of Advanced Science and Engineering (ASE) in a number of ways. It will use the national distributed super-computing infrastructure, enhance the use of such infrastructure through new modeling and visualization algorithms, and develop distributed visualization algorithms that drive displays from a compute cluster. It will fuse simulation data with experimental data captured from multiple sensors. It will develop strong connections with biology, engineering, and education through real scientific applications, computational modeling, and innovative course development. It clearly builds on several of the technical focus areas. It enables new forms of scientific research by integrating distributed experimental and simulation data (dmc+sim), developing new simulation capabilities (sim), and creating new human-computer interaction and visualization techniques for leveraging human intelligence (int).

Education and Outreach. The project will provide undergraduates, graduate students, and post-docs with the opportunity to work on several truly interdisciplinary projects. Interdisciplinary projects provide challenges that are not often found in research within a single discipline. Hands-on exposure to these challenges is one of the best ways to learn how to carry out such projects in the future.

A new class, "Visual Design for Immersive Scientific Visualization," will be tightly connected with this project. Students will be from both visual design and computer science backgrounds and will learn about collaborating with each other and with domain scientists to solve real scientific problems. Their design results will also feed into our evaluation framework.

A second new class, "Interdisciplinary Scientific Visualization" will help develop collaborations that involve fundamental information technology research that enables new scientific modes of inquiry. The class will be closely associated with the research effort we propose and will help to train students who will work on it. The project will also provide an ongoing source of ideas for class projects.

The Museum of Comparative Zoology at Harvard University has active outreach programs to K-9 students, and we will collaborate with them to bring the results of our research to a broader audience. Breuer has already published educational materials in Multimedia Fluid Mechanics [Breuer et al., 2000; Samimy et al., 2004], illustrating the complexity of fluid flows and presents them in a form that is compatible with the understanding and teaching of the complexities of fluid mechanics.

Undergraduate Research and Education. Brown has a tradition of involving undergraduates in the research process. In fact, the PI was an undergraduate researcher at Brown in the early 80's and was influenced strongly to pursue a scientific career. The tradition continues; we propose to involve undergraduates in this research to give them the sense of accomplishment and excitement that comes from working on a real-world problem and from making discoveries about the world. We have a very active undergraduate research contingent in computer science, biology, and engineering, and an ongoing effort to attract and involve more students. Opportunities are well advertised on departmental web pages and via word of mouth. The following publications from our research groups have included undergraduate authors: [DaSilva et al., 2000; Zhang et al., 2000a,b; DaSilva et al., 2001a; Laidlaw et al., 2001b; Zhang et al., 2001b,a; DaSilva et al., 2001b; Jackson et al., 2002; Peng and Forsberg, 2002; Weinstein et al., 2002; Laidlaw et al., 2004]. We have found that the focus on undergraduate research involvement can also help address the problem of under-representation of women in computer science by involving them in a mentoring relationship early in their college years.

2 Research Goals, Background, and Significance

In this section we give an overview of the work we propose and its significance. The following sub-sections describe first the scientific questions that will be addressed in the three application areas and the experimental data that will be acquired. They then move on to describe work simulating fluid-structure interactions, modeling uncertainty in flow simulations, and modeling flow fields that fill in gaps in experimental data. Visualization of complex flow and motion datasets, both simulated and experimental, is essential to understand and characterize the flow and motion. We describe how we will develop new visualization methods as well as our approach for characterizing and evaluating the visualization methods and environments. Milestones are described in more detail in Sec. 3.

Bioflow Applications.

Flow, Lesions, and Thrombosis in Coronary Arteries. The epicardial coronary arteries are rich in sites where atherosclerotic plaques form and enlarge. These branched blood vessels also flex during each heartbeat. In the acute phase of special clinical interest there are portions of the inner artery walls called the plaque caps that rupture [Richardson et al., 1989]; there is an increased risk of this in the first few hours of each day [Tanaka et al., 2004]. A type of blood clot, the platelet-rich thrombus, forms at the rupture. This clot may grow to block the vessel, or may episodically fragment partially. We want to visualize the associated fluid-mechanical processes - a level of complexity beyond previous achievements in visualization. We have been gathering tools and models for representing the arterial lumenal surfaces [Richardson, 2003b], unsteady flow in branched arteries [Sobel et al., 2002, 2004; Forsberg et al., 2003], thrombus initiation and early growth [Pivkin et al., 2003a], and arterial wall mapping [Guo, 2000; Guo and Richardson, 2001]. We plan to extend the range of flows we have computed, include some where the lumen is constricted, and using visualization techniques we will select a range of possible plaque cap fissure sites and through computation (developed from the model of [Pivkin et al., 2003a]) compute and display early thrombus growth, which will promote our development of added visualization modalities.

Animal Locomotion in Fluids. A key goal of research in organismal biology is understanding the functional design of life. How are organisms constructed, how do they function mechanically and physiologically, and how do these functions relate to the environments that organisms inhabit? One arena in which significant progress has been made over the past 20 years is the study of the functional design of organisms living in fluids [Vogel, 1994a,b, 2003]. The study of fluid flow is central to our understanding of organismal function. Organisms directly influence the surrounding air or water as they capture energy, locomote, and reproduce. Understanding how organisms influence fluid motion

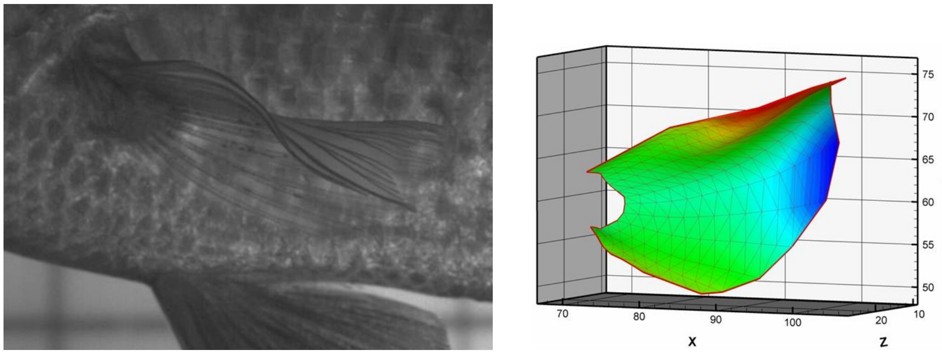

Figure 1: (Left) Side view of the pectoral fin of a sunfish during steady swimming at 0.5 body lengths per second. All locomotor thrust at this speed is produced by the pectoral fins. Note the complex fin shape as it moves out from the body. (Right) 3D fin conformation of the sunfish pectoral fin during steady swimming. This figure was generated by digitizing 350 points on the surface of the fin, and shows the fin position at an earlier time in the fin beat cycle than the image on the left.

is critical to testing hypotheses of adaptation, reconstructing patterns of evolution, and understanding organismal physiology.

The study of air and water flow patterns resulting from locomotion is a major endeavor in animal biology. As animals move through air and water, they generate complex 3D patterns of fluid movement that reflect this application of force to the environment. Understanding these patterns of fluid movement is critical to uncovering the fluid dynamic mechanisms that govern flight and swimming, the primary means of locomotion for the vast majority of animal species.

Kinematics and Experimental Hydrodynamics of Fish Locomotion. When organisms move about on land, the limbs generate force against the ground. Measuring these forces has been relatively easy, and considerable progress has been made in understanding locomotor dynamics [Alexander, 2003; Biewener, 1990; Cavagna, 1975]. However, for organisms moving in water, the quantification of forces produced by the body or fins has proven to be extremely difficult as water does not provide a stable platform for force measurement [Lauder, 2000b]. And yet measuring such forces is critical to testing biomechanical hypotheses of locomotor function in fishes, to understanding how muscles power swimming movements, and to understanding the relationship between body and fin movements and fluid motion. During the past five years, considerable progress has been made in applying the engineering technique of digital particle image velocimetry (DPIV) to freely-swimming fishes [Drucker and Lauder, 1999; Lauder and Drucker, 2002]. DPIV provides quantitative experimental 3D flow measurements within one or more 2D planes. This technique allows functional biologists to quantitatively characterize the water flow field behind swimming fishes, in the wake of fins, and over the body surface during natural locomotor behaviors. As a result, classical hypotheses about the functional significance of fish fin shapes and positions that have existed in the literature, in some cases for over 100 years, have been finally tested experimentally [Drucker and Lauder, 2001a; Nauen and Lauder, 2001b].

Relating the patterns of water flow in the wake of the body and fins to specific patterns of fin movements has proven more difficult. Kinematic studies of body and fin motion have to date been rather low resolution (both temporally and spatially) and as a result the linkage between biological movement and fluid motion is not well understood [Lauder et al., 2002a].

The goal of research on fish locomotion will be to generate an integrated kinematic and fluid dynamic data set so that hypotheses concerning fish fin function can be tested using our new visualization and analytical tools. By recording patterns of fin motion with two high-speed video cameras with a resolution of 1024x1024 or greater, details of fin motion can be seen that have previously not been amenable to analysis. For example, Fig. 1 shows a sunfish pectoral fin as it moves away from the body, and the wave of bending along the fin can be clearly seen. Previous analyses [Gibb et al., 1994; Walker and Westneat, 2000; Westneat, 1996] have treated the fin as a flat plate that can pivot as a whole, but with no span-wise flexibility. Fig. 1 also shows the reconstructed shape of the fin in 3D at one time in the fin beat that results from digitizing nearly 350 points in each of two camera views in a preliminary analysis of fin kinematics. The pectoral fin clearly is complexly deforming during movement, and such motions have clear potential importance for understanding how fluid forces are generated. But the complexity of motion has yet to be determined throughout the fin beat and during changes in speed and during maneuvering. Furthermore, detailed studies of fluid motion induced by these fin movements are needed to understand how the fin transmits momentum to the water.

Experiments will be conducted on freely swimming bluegill sunfish (*Lepomis macrochirus*) and rainbow trout (*Oncorhynchus mykiss*) swimming in a recirculating flow tank. Two high-resolution video cameras currently in the lab

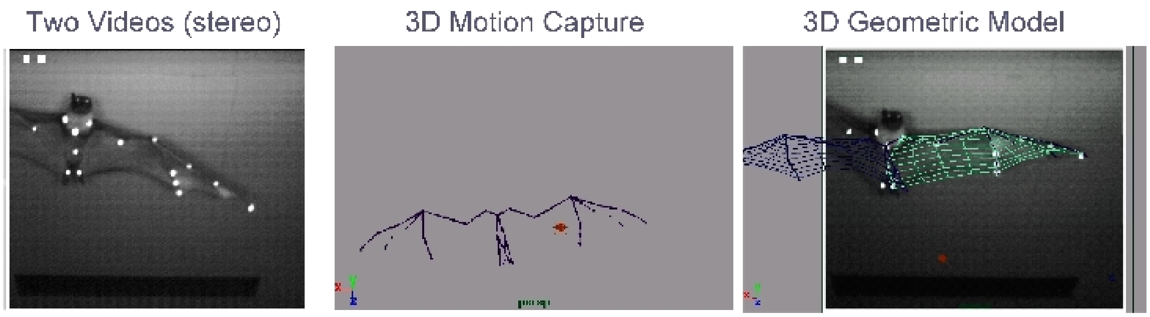

Figure 2: Video capture of bat wing shape changes.

will be used to obtain kinematic data, while a third camera will obtain the DPIV data on fluid flow patterns over the fin and in the wake.

The measurements of fin motion and water flow patterns using DPIV in the experiments proposed here will be used to test the following hypotheses. First, during pectoral fin locomotion in sunfish, the pectoral fin will support attached leading and trailing edge vortices which provide thrust early in the fin beat and minimize vertical oscillation of the center of mass. Second, fins with lower aspect ratio, such as those in trout, will not generate attached vortices during the first half of the fin beat due to the limited vertical range of motion and limited independent mobility of the fin ray elements supporting the fin. Third, fin surface flexibility enhances the transfer of net lift and thrust forces to the fluid by reducing drag and promoting vortex attachment.

Mechanisms of Bat Flight. Application of fluid dynamic approaches has revolutionized understanding of insect flight, revealing aerodynamic mechanisms almost unimaginable only 25 years ago [Dickinson, 1996; Dickinson and Gotz, 1993; Dickinson et al., 1999; Dudley, 2000; Ellington, 1984, 1991, 1996; Vogel, 1967; Willmott et al., 1997]. Although the flight of bats and birds is at least as likely to reveal insights of use in future technological application, such as the development of unmanned micro-air vehicles [Ellington, 1999; Spedding and Lissaman, 1998], students of vertebrate flight are just beginning to incorporate sophisticated methodology drawn from physical and mathematical sciences [Rayner et al., 2001; Spedding et al., 2003; Tobalske et al., 2003]. Documenting the structure of airflow around wings that not only flap, but also undergo enormous shape changes in each wing-beat, poses significant technical challenges, as does visualizing the complex 3D data such studies necessitate.

The unique features of bats - their specialized skeletal anatomy, the high degree of muscular control of wing conformation, and their highly deformable wing membrane skin - yield wings that undergo large changes in 3D geometry with every wing-beat cycle, and consequently, highly maneuverable and energetically efficient flight [Winter et al., 1998; Voigt and Winter, 1999; Stockwell, 2001; Swartz et al., 2004]. To date, however, bat flight has not been studied from the quantitative perspective of unsteady aerodynamics. In particular, there is no rigorous understanding of the mechanisms by which the bat is able to generate the high aerodynamic coefficients necessary to execute its flight capabilities, or of the vortex structure associated with the exquisite aerodynamic control that bats exhibit.

Progress in understanding the relationships among wing shape, movement, and airflow during bat flight requires interdisciplinary collaboration of the kind proposed in this project. The goal of our work will be to integrate spatially and temporally detailed kinematic analyses of several kinds of bat flight with both experimental studies and computational simulation of the flow patterns generated during flight.

Our studies will differ fundamentally from previous studies of bat flight in important ways. First, the visualization approaches we will employ will allow the first characterization of bat flight kinematics that does not treat the wings as simple oscillating plates, but instead will explicitly characterize changing intrinsic wing structure of potentially great aerodynamic importance. Second, we will employ DPIV methods to describe flow structure and relate dynamics of 3D wing form to evolution of wake structure during the wing-beat. Third, we will employ the realistic wing geometries captured in computational simulations of airflow using $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$, a computational fluid dynamics package, and be able, for the first time, to compare experimental measurements of flow structure with numerical simulations.

Our work will begin by using flow visualization to identify the aerodynamic mechanism of the unique flight of bats. As we gain insight into the mechanistic basis of bat flight from direct experimentation, we will be able to evaluate the relationship between numerical flow simulations and experimental data via the following four questions: 1) Is the overall pattern of flow structure around flying bats similar in simulation and experiment? 2) Are specific wake structure in similar locations? 3) To what degree is the timing of flow development similar? 4) Is the magnitude, spatial orientation, and timing of aerodynamic force production comparable?

We propose to answer these questions in the context of two sets of comparisons, one of a single species (*Rhinolophus megaphyllus*) flying at a variety of speeds, and a second of individuals from five species that differ primarily in (i) wing shape, (ii) body size, and (iii) evolutionary history [Murphy, 2001; Norberg, 1987, 1990; Springer, 2001; Teeling, 2000, 2002]. These comparisons will, we believe, be particularly helpful for addressing the many uncertainties in the theoretical formulations of the existence, mechanics, and energetics of hypothesized gaits in flying vertebrates [Hedrick et al., 2002; Rayner, 1999; Spedding, 1986, 1987, 1992; Spedding and Pennycuick, 2001; Spedding et al., 2003; Willmott et al., 1997; Tobalske, 2000; Tobalske and Dial, 1996; Tobalske et al., 1999]. We will simultaneously record wing geometry changes and flow in the wake of the flapping wings by employing linked image-capture systems (see Fig. 2).

These goals both require and contribute to the development of the visualization and analysis tools proposed. For example, to take advantage of computational simulation of flow around flying bats, it is essential to validate simulations with rigorous experimental measurement of in vivo flow over the wings and in the wake. However, DPIV and $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ simulation data differ in some critical respects. For example, DPIV data are typically 2D rather than 3D, and the sampling plane must be chosen before experimentation commences. Modeling tools for filling in the gaps between 2D sections and visualization tools for examining and characterizing 3D flows therefore have the potential to dramatically increase the value of both kinds of data when they facilitate greater ease in comparison among them.

Flow-Structure Simulations. We will undertake a high-order accurate simulation of fluid-structure interaction by coupling a parallel spectral/*hp* element fluid solver $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ with the hp-FEM solid solver StressCheck[1]. The objective is to perform direct numerical simulation (DNS) of flows past lesions in arteries, past swimming fishes, and around flying bats using realistic representation of flows and structures.

The Fluid Solver - $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ and the Structural Solver - StressCheck. The flow solver used in this study corresponds to a particular version of the code $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$, which is a general purpose CFD code for simulating incompressible, compressible and plasma flows in unsteady 3D geometries. The algorithmic developments are discussed in Karniadakis and Sherwin [Karniadakis and Sherwin, 1999] and Kirby et. al [Kirby et al., 1999b]. The *discontinuous Galerkin* method for solving the 3D, unsteady, viscous compressible Navier-Stokes equations as presented in Lomtev et. al [Lomtev et al., 1999] was employed. The code uses meshes similar to standard finite element and finite volume meshes, consisting of structured or unstructured grids or a combination of both. On each "macro" element a 3D polynomial expansion using orthonormal Jacobi polynomials of variable order p is used. Hence, we can capitalize on the dual path to convergence which these methods allow - increasing the number of elements used (h-refinement) *and* increasing the polynomial expansion order on each element (p-refinement). The former type of refinement admits algebraic convergence while the latter, under certain regularity constraints, admits exponential convergence.

StressCheck is a commercially available hp-version finite element solver [Szabo and Babuska, 1991] for accomplishing linear and nonlinear structural analysis. It has been chosen because of its advantages: a) it provides an error estimator to assure the accuracy of the computed data, b) it provides 3-D "thin solid" elements [Szabo and Sahrmann, 1988] without the need for modeling assumptions usually used in other codes, c) it enables the use of elements with very large aspect ratios, a mandatory requirement in the simulation of thin wall structures, d) it is the only hp-FEM code enabling geometric non-linear capabilities [Noel, 1996] such as would become influential when a wing undergoes typically large deformations during flight, e) it provides a Component Object Model (COM) interface through which the coupling to the fluid solver is convenient.

Fluid-Structure Coupling. $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ solves the fully 3D viscous compressible Navier-Stokes equations, and the pressure and shear stress distributions on the structure are extracted. The fluid-structure coupling is achieved by an Arbitrary Eulerian Lagrangian (ALE) formulation, which allows "arbitrary" motion of the fluid-structure interface. The interaction is accomplished by incorporating the instantaneous pressure and shear stress distribution on the structure with the resultant deformation obtained through the structural analysis by StressCheck.

Modeling Uncertainty. In realistic simulations there are many sources of uncertainty associated with boundary and initial conditions, geometry representation, transport properties, and constitutive relations. These uncertainties can change results quantitatively or qualitatively, introducing or hiding potentially important behavior. Knowing the uncertainly can be essential to understanding a flow example. We propose to employ stochastic simulations to propagate uncertainty through the nonlinear flow models using generalized polynomial chaos (GPC) [Xiu and Karniadakis, 2002]. This technique is orders of magnitude faster than even accelerated Monte Carlo methods, especially for correlated stochastic inputs. The stochastic output will also be used to study the sensitivities of the systems, which are simply the generalized derivatives of the solution with respect to the stochastic input. Therefore, in a single simulation

[1] StressCheck is a Trade Mark of Engineering Software Research & Development, Inc., 10845 Olive Blvd., St. Louis, USA

we will be able to decide on the relative importance of the uncertain inputs so that we pursue further probing of the flow system.

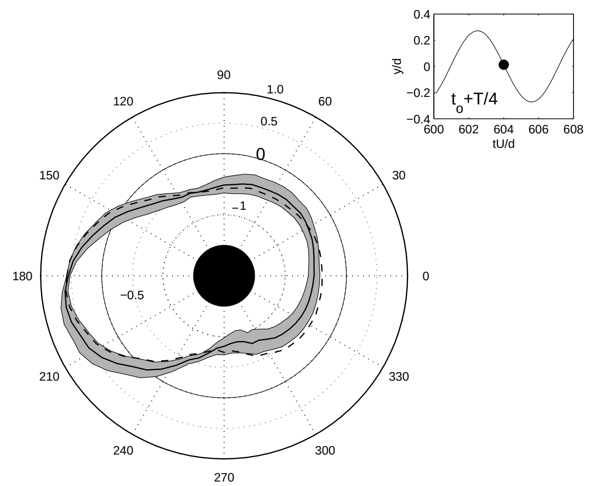

Figure 3: Polar plots of instantaneous pressure distribution on the cylinder surface relative to the cylinder $mean$ cross-flow position. Deterministic pressure solution (dashed line); Stochastic pressure solution (solid line and shaded area).

Numerical Solution and Preliminary Results. The final equations are a set of deterministic coupled equations obtained by standard Galerkin projection of the governing equations into a space spanned by the Askey polynomial basis [Askey and Wilson, 1985]. Applying this to the incompressible Navier-Stokes equations, we obtain a set of couple deterministic modified Navier-Stokes equations that we can solve with standard techniques. An application of GPC is shown in Fig. 3 that shows a stochastic simulation of flow past a circular cylinder subject to inflow noise, i.e. uncertain inflow conditions. We see that the pressure on the cylinder is a distribution with a mean value that differs from an equivalent deterministic prediction. We also plot the corresponding error bar associated with the variance of the stochastic pressure function.

Modeling Gappy Data. While data assimilation is routinely used in climate and ocean modeling, this is not the case with more classical fluid mechanics applications. However, the recent rapid developments in quantitative imaging techniques like DPIV and the simultaneous advances in large-scale simulation open the possibility for seamlessly integrating simulation and experiment.

We propose to apply and extend work done by Karniadakis and collaborators on low-dimensional modeling for fluid flows using proper orthogonal decomposition (POD). Specifically, we will generalize a technique recently developed in [Venturi and Karniadakis, 2003] for reconstructing complete flow fields from gappy data. The incomplete fields are created from DNS snapshots of flow past a circular cylinder by randomly omitting data points. We follow a method first proposed by Everson & Sirovich (1995) and extend it so that it produces the maximum possible spectral resolution independent of the initial guess for the fill-in elements. We simulate two levels of gappiness at approximately 20% and 78%, and find that all energetic scales are captured even for the higher level. This new methodology can be a building block in an effort of developing effective data assimilation techniques in fluid mechanics applications. The new extension is the ability to utilize gappy data from experiments or partial DNS data or a combination of both. This will allow us to incorporate DPIV data usually obtained for small flow subdomains into full-scale simulations using POD modes at least partially extracted from real data in the spirit of work presented in [Ma et al., 2003; Sirisup et al., 2004].

At the heart of this integration is the ability to reconstruct flow fields from a finite number of experimental observations at a *controlled* level of accuracy. This problem is, of course, not new, and researchers have been working on it for many decades. One of the first effective approaches was developed by Yates in 1933 [Yates, 1933] who proposed filling-in missing data with least-squares estimates. Several statistical approaches for data imputation building on the original ideas of Yates are presented in [Little and Rubin, 2002].

In this work we follow a deterministic approach based on proper orthogonal decomposition combined with the least-squares approach first proposed in [Everson and Sirovich, 1995] for image reconstruction. It has been used with success in [Tan et al., 2003] for steady flow past an airfoil. Here we apply this method to *unsteady* flow past a circular cylinder and investigate ways of improving its performance. The fundamental question is what is the *maximum* possible resolution that can be achieved given a certain degree of gappiness in the data. This is a rather complex issue, however, the proper orthogonal decomposition provides the best representation (in the average sense) for a given field and produces a hierarchical set of spatio-temporal scales. This, in turn, helps in establishing accuracy criteria and thus it addresses the question of maximum possible resolution. Indeed, in the current work we have extended the Everson-Sirovich approach in a way that leads to the best possible reconstruction independent of the initial guess for filling-in the missing data.

We have selected the flow past a cylinder as a test problem due to the previous experience with this flow that shows that a low-dimensional representation indeed exists [Ma et al., 2003; Cao and Aubry, 1993; Deane et al., 1991]. We have investigated two states at Reynolds number 100 and 500 (based on the cylinder diameter) and two degrees of

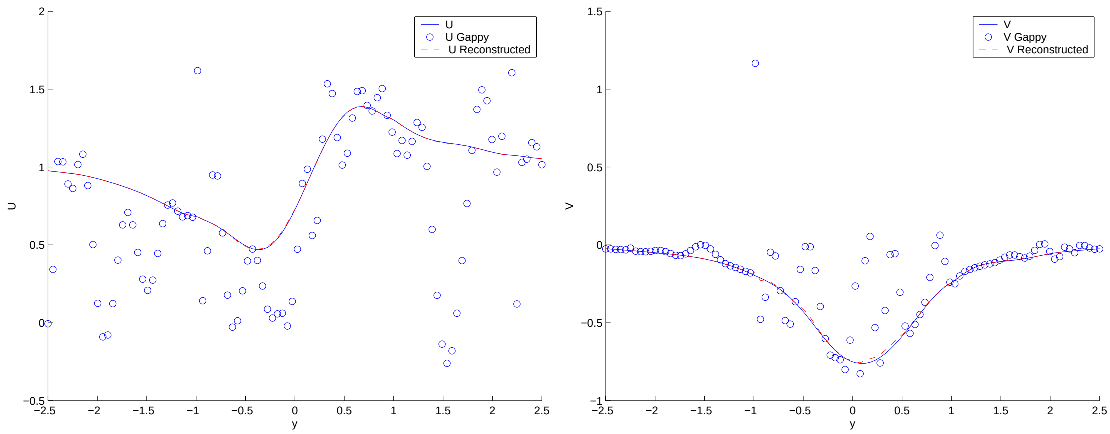

Figure 4: Reconstruction of velocity field at $Re = 500$. Shown are the gappy data for the two velocity components, and the "true" and reconstructed instantaneous profiles at a location eight diameters behind the cylinder.

gappiness at approximately 20% and at 78%. In Fig. 4 we show a typical result of the reconstruction at $Re = 500$. We see that a very good agreement is achieved between the reconstructed velocity profiles and the "true" profiles for gappiness of 20%.

POD Theory and Gappy Data. Let us consider a vector flow field $\mathbf{u}(\mathbf{x}, t) \in \left(L^2(\Omega \times T)\right)^d$, where d is the number of the components of the vector field defined on the spatio-temporal domain $(\Omega \times T)$. We assume that we have available a finite number N of snapshots of the flow field. We can then look for a *biorthogonal representation* of $\mathbf{u}(\mathbf{x}, t)$ in the form

$$\mathbf{u}(\mathbf{x}, t) = \sum_{k=1}^{N} \lambda_k \Phi_k(\mathbf{x}) \psi_k(t), \tag{1}$$

where $\Phi_k(\mathbf{x})$ and $\psi_k(t)$ are the orthonormal spatial and temporal modes, respectively.

The unknown functions $\Phi_{\mathbf{k}}(\mathbf{x})$ and $\psi_k(t)$ can be calculated by minimizing an energy functional, producing a POD or Karhunen-Loeve decomposition. The solution produces a list of orthogonal modes sorted by importance, much as does principle component analysis.

The formulation assumes the completeness of the flow field in the spatio-temporal domain. However, modifications are required if there exists a space-time region in which the field $\mathbf{u}(\mathbf{x}, t)$ is missing or is corrupted leading to incomplete dynamics. We would like to reconstruct this gappy field using the POD orthogonal modes. This is the problem first considered in [Everson and Sirovich, 1995] for a static image reconstruction problem.

The procedure proposed by Everson & Sirovich completes the missing space-time dynamics starting from a certain initial guess for the unknowns and proceeds iteratively. At the heart of the method is again the minimization of a functional but in a new norm, defined on the space-time domain where the field is known. Let us denote by $\tilde{\mathbf{u}}(\mathbf{x}, t)$ a completed field obtained based on some initial guess. The Everson-Sirovich procedure employs the average value at that location as the initial guess. Subsequently, we iteratively perform POD decomposition of $\tilde{\mathbf{u}}(\mathbf{x}, t)$ and use some of the modes of the decomposition to revise the *guessed* spatial and temporal data within gaps.

We have developed the following extension of the Everson-Sirovich procedure that, as we will demonstrate, does not depend on the initial guess. We summarize here the main steps of the modified method: 1) Perform the standard Everson-Sirovich procedure but employ only two modes in the reconstruction. 2) Use the converged result from the previous step as a new initial guess and apply the Everson-Sirovich procedure but now employ three modes in the reconstruction. 3) Proceed similarly for the n^{th} iteration until the obtained eigenspectrum does not change anymore.

Although more costly, this iterative procedure leads to the maximum possible resolution of the true eigenspectrum and thus of the accuracy in reconstructing the flow field. The final solution will only depend on the degree of gappiness. Alternatively, one could stop at an earlier iteration if accurate resolution only of the first few modes is desired.

Visualization Synthesis, Characterization, and Evaluation. Driven by the biological applications and using simulation results together with experimental data and estimates of uncertainty, we will synthesize new visualization methods, implement existing methods, identify a set of visualization goals for such methods, characterize existing and new methods relative to those goals, coalesce the characterizations into more complete evaluations, and use the knowledge gained to iterate on better visualization methods both manually and automatically. These visualizations will target captured kinematic motion of arteries, fishes, and bats; captured and simulated fluid flow around these prescribed geometries; and comparison among different datasets. They should help in evaluating scientific hypotheses, in observing the phenomena in an environment where they can be studied extensively, and in generating new scientific hypotheses and insights.

Visualization Synthesis. Our creative visualization synthesis efforts will be within our research group, with visual designers from the Rhode Island School of Design (RISD), and via a novel scientific visualization class co-taught between Brown and RISD. Our research group has developed several novel and effective display methods for multi-valued datasets representing complicated 3D time-varying phenomena [Wenger et al., 2002; Weinstein et al., 2002; Hueso, 2003; Karelitz et al., 2003a; Sobel et al., 2004; Forsberg et al., 2000]. We will build on these efforts. Part of that process will include visual design experts from among the faculty and student body of both RISD and Brown. These experts will provide critical feedback as well as advice and sketches for new ideas. We will also continue to study artistic motivations for new visualization methods [Vote et al., 2003]. Perhaps most interesting, we will also teach a joint Brown/RISD class consisting of half Brown Computer Science students and half RISD design students. In this class, the students will collaboratively execute a number of design exercises, learn about 3D time-varying fluid flow, study the "medium" of virtual reality, and culminate in a set of new visualization methods directly targeting the bioflow application efforts of this proposal and utilizing the experimental data and simulation results and uncertainty estimates of earlier sections.

Visualization Design Tools. One of the challenges of incorporating visual design experts into the visualization synthesis process is providing them with ways to meaningfully contribute. They must understand the scientific problems, the visualization design problem, and the medium; we will teach all of these in our class. While they can contribute via critical feedback and prototype designs done with traditional media; they can do so only to a limited degree. Traditional media do not capture the immersive qualities and interactive potential of state of the art visualization environments. Thus, critiques based on designs created with these media are of limited utility in converging upon a final visualization. To contribute more directly and significantly expert designers must either learn how to develop software or have tools that let them create within the target visualization environments. We will continue to develop such tools. Some will ease the process of importing animation and geometric models into the visualization environment. Some will permit sketching of new visualization ideas in virtual reality; these will be derived from CavePainting [Keefe et al., 2001; Karelitz et al., 2003b], an application for artistic expression in virtual reality. We will extend the application to facilitate quick visualization prototyping with varying degrees of connection between the prototypes and underlying data.

We will address several important computer graphics and interaction research questions which are key in developing these collaboration-enabling tools. Our experience with the CavePainting system and its use in multiple artistic collaborations, including the initial Brown-RISD visualization design class, has enabled us to identify these key areas.

First, how can designers achieve a precise level of control over 3D creation of line and form? CavePainting uses a paintbrush prop whose position and orientation are both tracked. Artists move it through the air to immediately create 3D virtual lines and form. Since the "painting" is done directly in 3D, with no canvas or table upon which to push or rest one's arm, achieving precise control over one's arm movements and thereby the form of virtual marks can be a difficult task. We will examine alternative interactions and form factors for this task, including desktop VR setups, haptic feedback interaction devices, and two-handed input techniques that build on Buxton et al.'s digital experiments with tape drawing [Grossman et al., 2002; Balakrishnan et al., 1999], a technique commonly used in the car design industry.

Second, what computer graphics rendering strategies are appropriate for prototyping scientific visualization designs? The methods that we will implement will be a great aid to collaborative efforts as they will allow scientists to see past the potentially unfinished, sketchy quality of a design to examine and comment on its scientific potential. All of this will happen directly within the target visualization environment, enabling important critiques where visualization form factor and interaction are considered. Developing appropriate rendering techniques which achieve this feeling while remaining truthful to the data and scientific problem at hand is an open research problem.

Third, to what extent should design tools be linked to and controlled by data? A strong link with the data may enable drawings to morph in response to time varying data or snap directly to flow lines or other features. As feature detection algorithms continue to develop, we may be able to establish strong correspondences between strokes in a design drawing and important recognizable flow features, such as vortex core lines or shock rings. On the other hand, a tight coupling of a drawing or other artistic expression tool to scientific data can significantly constrain the tool and limit design freedom. It is important to avoid over-constraining visual designers in this collaborative process, since

Figure 5: Artistic inspiration for scientific visualization. (Left) *The Gold of Azure*, 1967 by Joan Miró. (Right) The painting on the left by Joan Miro was used to inspire the visualization of bat flight data produced using CavePainting software in our virtual reality Cave.

this may leave little opportunity for designers to create the types of novel visualization ideas that are often required in difficult, 3D, time-varying, multivariate visualization problems.

Fourth, what additional resources do visual designers need in order to facilitate the design process for scientific visualization tools? Traditional media offer means for continued work on a design problem over time. When painting, a design is often refined by layering paint on top of previous layers. The artist works *from* the existing layers of design; they provide inspiration and guides. However, the final design actually covers up the initial designs. This is a natural and intuitive method of refining a design, but it has no analogue in 3D visualization design. Currently, our methods for evolving design are closer to the technique of: make lots of drawings, then pick one. Of course, this process also exists in traditional media. Artists often make initial drawings, or studies, for finished works. Each study focuses on a different aspect of the design or represents a refinement of a previous sketch. We can mimic this process with our current tools, but it is often more difficult than the analogous traditional process because of the technical limitations of our media. For example, artists almost never work from scratch, without an existing physical model, picture, or study drawing. When we walk into a Cave, we are shut off from the rest of the world. Even bringing something physical into the Cave as a resource is problematic, since the Cave room needs to be kept dark. We are left to create designs in something like an application specific vacuum. At the very best, our starting point is a 3D model that represents the geometry of our scientific problem. This simply makes the process of artistic refinement more difficult than one feels it should be. As an initial exploration into addressing this issue we have developed tools, based on the concept of drawing inspiration for visualizations from oil paintings [Kirby et al., 1999a; Vote et al., 2003], that enable artists to import regions of inspirational paintings as graphic textures and use these to create new 3D visualization designs. Fig. 5 shows an initial design for a fluid flow visualization around a bat in flight along with the Miro painting which inspired it.

Uncertainty Visualization. A new focus of our work will be to represent uncertainty in the visualizations that we create. The simulation results that we will produce will include uncertainty information, and we will also quantify measurement error in the experimental data that we collect. A number of approaches have been explored for uncertainty visualization [Pang and Sheehan, 1996; Pang and Lodha, 1996; Pang et al., 1997; Interrante, 2000; Djurcilov et al., 2001, 2002], and Johnson reviews and compares many of them in [Johnson and Sanderson, 2003]; we will implement and test some of those methods and use our methodology for representing multi-valued data, adding uncertainty as another quantity within our visualizations.

Characterization and Evaluation of Visualization Methods. We will develop a framework for characterizing the efficacy of visualization methods. User studies are generally recognized as an effective evaluation approach; we and others have employed them on visualization methods [Healey and Enns, 1999; Ware and Franck, 2000; Laidlaw et al., 2001b; Kosara et al., 2003; Jackson et al., 2003; Laidlaw et al., 2004], and we will continue to do so. While these methods can be effective, they tend to permit only very specific measurements that do not always generalize well. We will also develop a new visualization evaluation approach that builds on user-study methodology but that has the potential to answer broader questions about visualization efficacy. It is also likely to generate results that generalize better. Rather than measuring user performance on short, quantifiable tasks, we will acquire subjective evaluations of visualization methods by visual design experts. We have piloted this kind of study in comparison with an objective and quantitative user study and found that the results are comparable with many fewer users [Jackson et al., 2003].

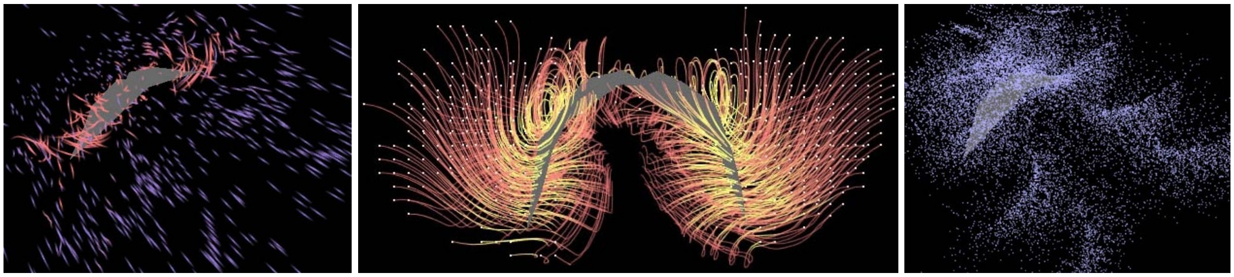

Figure 6: Three different visualization methods are used to show different characteristics of the structure of the simulated flow around a motion captured bat [Weinstein et al., 2002; Hueso, 2003]: (left to right) particle eels are used to display pathlines, time-varying streamlines show vortices atop the wing during a down beat, and white dots capture structures in the wake.

Expert designers will evaluate the ability of visualization methods to show flow features in a set of well-characterized time-varying 3D flow cases. One of the challenges in developing flow visualization methods is that the methods need to display not only flow structures and flow-body interactions that are expected, but also those that are unexpected or even unknown.

We will develop a set of 3D flow visualization design goals, and, for each visualization method, we will characterize its performance against those goals. Many of the design goals will involve the effectiveness of a method to display flow structures and flow-body interactions in well-understood flows, such as 3D cylinder flow at different Reynolds numbers. Some will involve the ability of methods to co-exist with other methods, displaying multiple features using multiple methods in a single combined visualization. Other goals will be more abstract, attempting to capture the ability of a method to show the "gist" of a flow, an overall synopsis of what is going on and why. We also expect to discover additional design goals and to incorporate them into our characterization framework. The need for these design goals is likely to arise as we apply the methods to our bioflow applications, where the flows are not understood.

A major challenge in this process will be adjusting the parameters of each visualization method. Typically, each method has a number of parameters that influence its appearance. For example, a 2D vector visualization with arrows on a regular grid might have a parameter that control the relative lengths of the arrows and another that controls their spacing. The settings of these kinds of parameters influence the efficacy of a method. In fact, good parameter settings for one design goal can be poor for another. We will capture these parametric differences in our characterization of visualization methods.

The results will be a body of knowledge that will guide us to effective visualization methods in a number of contexts. In one context, we may find that a certain hybrid of visualization methods is effective for studying bat flight at one Reynolds number. Another species of bat, or of fish, may require different design goals, and so a different combination of visualization methods may be appropriate. Fig. 6 shows a set of different visualization methods displaying the structure of simulated flow around a motion-captured bat. Note that different methods capture different types of features well.

Visualization Optimization. While manual use of this body of design knowledge will help identify good visualization methods, we also propose to automate the process, creating a visualization framework that aggregates design knowledge and then uses it to search a space of possible visualizations. We are currently exploring this approach for generating 2D visualization of multi-valued data. For this 2D system, we have defined a language for specifying layered 2D visualization methods. Each method is represented by a point in a parameterized space of possible visualizations. Much as with the characterization work, expert visual designers quantitatively evaluate or score example methods, also providing suggestions for improving the methods. These suggestions for improvement imply a direction to move within this space of possible visualizations in order to improve our score. We have codified this into a gradient of the score, and expect that it will dramatically speed the optimization process. The scoring process will be done iteratively, with software generating new visualization methods and designers scoring them until a "good enough" method is achieved.

3 Research Plan

In this section we propose year-by-year milestones to realize the vision proposed above. The year-by-year milestones are presented separately for each of the disciplines.

Visualization Synthesis, Evaluation, and Optimization.

Year 1. Recruit and hire personnel and set up software development and data management infrastructure. Identify and implement existing visualization methods to evaluate, including some of our own that are already implemented; each will have a number of parameters which will be part of the design process. Create tools for designer prototyping of visualization methods. Run visualization design class and get new visualization method ideas as well as new potential designer participants. Identify a set of canonical well-known flow cases that will help characterize visualization methods; this will be done in collaboration with experts from engineering, fluids, biology, and computer science. Get simulations for those cases and create visualizations for those datasets. Begin to identify design goals for fluid and motion visualizations, again in collaboration with experts from all of our disciplines. The goals will be based on biology needs, on physics knowledge of fluid structures, on observing well-known flow cases, on ability to observe important flow structures, on ability to identify the certainty (or uncertainty) of features, and, as we progress, on observing all of the flow cases that we will work with. Develop tracking methods for capturing motion of fish fins.

Year 2. Capture and import motion information for bat wings and fish fins. Get fluid simulations of some bioflow cases for arteries, bats, and fish. Continue to collaboratively identify design goals for fluid visualizations, bringing in new knowledge from biological application areas as we observe captured motion. Subjectively characterize visualization methods on well-known flow cases for design goals; this will be done by design experts, biology users, flow experts, and visualization experts for desktop stereo without head tracking, initially.

Year 3. Continue to subjectively characterize methods on well-known cases for cave, desktop stereo with head tracking, desktop super-resolution stereo, and a stereo workbench. Experimentally verify some characterizations with quantitative user studies. Apply methods to early artery and bat flow datasets to validate characterizations and to begin getting biological results. Run visual design class, get new visualization methods from class, incorporate into evaluation system. Synthesize new or hybrid visualization methods with designer input; characterize methods in same framework as existing methods.

Design framework and language for specifying family of 3D visualizations; framework and language will be based on abstractions from existing methods and on layered 2D framework we've been developing. Begin production application of visualization methods to bioflows; iterate on design improvements and characterizations.

Year 4. Implement framework and language for specifying family of 3D visualizations. Develop framework for codifying effectiveness of methods for design goals. Run subjective user studies to capture design knowledge. Continue production application of visualization methods to bioflows; iterate on design improvements and characterizations.

Year 5. Run visual design class, get new methods from class, incorporate into visualization evaluation and production system. Use captured knowledge to automatically optimize visualizations built with language. Validate results from automatic optimization and contrast with results from manual system. Complete production application of visualization methods to bioflows.

Simulation and Modeling. The group of Karniadakis will be responsible for new developments in $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ both on the algorithmic as well as on the parallel implementation. In particular, two main thrusts will be pursued and integrated with the visualizations. (1) Uncertainty modeling, and (2) Low-dimensional representation. In the following, we provide details on these two new areas.

Year 1. Incorporate generalized polynomial chaos (GPC) into $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$. Pursue algorithmic work and parallel implementation. Start new algorithmic work in post-processing DNS or 3D DPIV data using proper orthogonal decomposition.

Year 2. Target flow-structure interaction uncertainty; model both inflow conditions and imprecise structural properties, e.g., modulus of elasticity and possible constitutive laws. Deal with gappy data and unsteady boundary conditions. Develop and test a penalty method to deal with boundary conditions, especially for data with a relatively small domain. Construct POD modes for both the unsteady bat motion as well as the unsteady fish motions and extract corresponding flow models consisting of 10 to 20 modes.

Year 3. Extend GPC methods to deal with multi-dimensional stochastic inputs. A key development here is the use of fast multipole transforms to deal with with resolution of the covariance kernels of very large dimension. Establish a new approach in extracting such kernels from point measurements so that a compact and efficient representation be formulated. Develop hybrid POD algorithms that provide the framework for interfacing 3D DPIV data with DNS.

Year 4. Extend GPC to visualizations with reduced data sets. Develop new algorithms to deal with sensitivity factors and output post-processing. Focus on the arterial flow modeling and POD models that predict near-by states for parametric studies in the CAVE

Year 5. Applications of the uncertainty and POD modeling will be pursued for the flow around the bats and the fish by fusing experimental data and simulations together. The final focus of the effort is the seamless integration of the stochastic and reduced-order simulations with the immersive visualizations with particular emphasis on the requirements for interaction.

Cardiovascular Hemodynamics.

Year 1. Refine model platelet behavior such that adhered platelets release adenosine diphosphate (ADP), initiating activation earlier. Observe changes in shape and timing of thrombus formation. Examine the effect of arterial narrowing with a stenosis level of 10%. Compute simulated flows and examine.
Year 2. Introduce a finite termination time of ADP release, an effect known to be associated with aspirin, and examine its effect on predicted thrombus formation as a function of blood flow velocity. Compute and visualize flow for higher levels of stenosis - 30% and 50%.
Year 3. Examine modeling of inter-platelet tethering (e.g., fibrinogen), which will allow torques to arise. Compute and visualize flow for higher levels of stenosis - 65% and 80%.
Year 4. Examine embolization, initially using a randomly-timed loss of continued adhesion by platelets, and again making comparison with available experimental data. Examine around the stenotic region the rate of thrombus growth to assess the capability of plaque cap fissuring location to influence the thrombus growth rate.
Year 5. Incorporate the effect of von Willebrand deficiency in the platelet model. Shift the location of the arterial narrowing to two locations fully downstream of the side-branch level; observe flow changes and relate to myocardial infarction.

Kinematics and Experimental Hydrodynamics of Fish Locomotion.

Year 1. Begin development of visualization tools for analyses of complex 3D fin motions in fishes. Begin experimental measurement of fin motion to generate the high-speed video sequences needed to refine the new visualization tools and to generate output variables for statistical analysis.
Year 2. Complete motion visualization program development. Analyze high-resolution high-speed videos of two species of swimming fishes using these new tools to obtain quantitative 3D data on fin motions at different swimming speeds and during maneuvering.
Year 3. Conduct experimental hydrodynamic experiments to quantify in high-resolution (5-10,000 vectors per 10 cm^2 area) the flow around the pectoral, dorsal, and caudal fins in sunfish and trout. Experiments will measure flows during both steady swimming at a variety of swimming speeds (from 0.5 to 2.5 lengths/second) and maneuvering locomotion. Develop experimental protocol to simultaneously obtain kinematic and hydrodynamic data.
Year 4. Complete experimental quantification of fluid flows around fish fins, and begin integration of these data with kinematic information. This will allow determination of the existence (or not) of attached leading edge vortices and the kinematic basis for vortex attachment. Coordinate data acquisition and analysis with the simultaneous development of visualization tools for 3D fluid flows by other team members.
Year 5. Complete analyses of fluid flow patterns, and final integration of kinematics and fluid mechanics for each fin in each species. Fine tuning of software that allows analytical and visual integration of kinematics and fluid mechanics.

Bat Flight.

Year 1. Begin experimental measurement of wing motions and shape change coupled to airflow dynamics in single species (*R. megaphyllus*). Obtain 'archetype' high-speed video sequences for input to research on new visualization tools. Begin exploration of velocity dependence of kinematic and flow characteristics. Begin construction of $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ models of constant-speed wingbeat.
Year 2. Analyze high-speed videos of bats during constant speed wind tunnel flights, using new visualization tools to obtain quantitative 3D data on motion and flow dynamics. Use parallel experimental and simulation datasets to stimulate visualization tool development for complex 3D dataset comparisons.
Year 3. Extend $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ simulation to broader range of flights, including diversity in speed, wing form, and body size. Employ comparison tools developed in Years 1-2 for validation and exploration of limits to computational simulations.
Year 4. Develop data capture methods for flights outside of wind tunnel environment, with special focus on hovering, acceleration, and turning. Begin kinematic and flow data acquisition for hovering, accelerating, and maneuvering.
Year 5. Complete analyses of alternative flight modes and explore feasibility of computational modeling of these more challenging flight maneuvers. Fine tuning of software that allows analytical and visual integration of kinematics and fluid mechanics, comparisons of experiment and simulation.

4 Results from Prior NSF Support

Laidlaw and Karniadakis. "ITR: Visualization of Multi-valued Scientific Data: Applying Ideas from Art and Perceptual Psychology," NSF award 00-86065, $2.3M, 9/00-8/04, PI: Laidlaw, Co-PI: Karniadakis.

Resulting publications: [Acevedo et al., 2000; DaSilva et al., 2000; Forsberg et al., 2000; Laidlaw, 2000; Tyszka et al., 2000; Vote et al., 2000a,b; Zhang et al., 2000b,a; van Dam et al., 2000; Acevedo et al., 2001; Ahrens et al., 2001a; Crisco et al., 2001; DaSilva et al., 2001a; Demiralp et al., 2001; Healey et al., 2001; Jacobs et al., 2001; Keefe et al., 2001; LaViola et al., 2001; Laidlaw et al., 2001b,a; Laidlaw, 2001; Rhyne et al., 2001; Schkolne and Keefe, 2001; Vote, 2001; Zhang et al., 2001b,a; Dhenian et al., 2001; Zhang and Laidlaw, 2001; Holbrook et al., 2001; Ahrens et al., 2001b; Ahrens and Readhead, 2001; DaSilva et al., 2001b; Grimm et al., 2002; Jackson et al., 2002; Marai et al., 2002; Rubin and Keefe, 2002; Turner et al., 2002; Vote et al., 2002; Woodhouse et al., 2002; Zeleznik et al., 2002; Zhang et al., 2002; van Dam et al., 2002; Narasimhan and Jacobs, 2002; Sadun et al., 2002; Ahrens et al., 2002; Ruffins et al., 2002; Pivkin et al., 2002; Crisco et al., 2003; Demiralp et al., 2003; Dube et al., 2003; Jackson et al., 2003; Karelitz et al., 2003b; Kosara et al., 2003; Marai et al., 2003a,b; McClain, 2003; Pivkin et al., 2003b; Rhyne et al., 2003; Ahrens et al., 2003; Koshibu et al., 2003; Sobel, 2003; Vote et al., 2003; Woodhouse and Turner, 2003; Zhang et al., 2003; Keefe et al., 2004; Laidlaw et al., 2004; Sobel et al., 2004; Zhang et al., 2004b,a; Draganski et al., 2004; Forsberg et al., 2003; Guo, 2000; Guo and Richardson, 2001; Pivkin et al., 2003a; Richardson, 2002, 2003a,b; Sobel et al., 2002; Tanaka et al., 2004; Wagner et al., 2004]

The work has also been described in several popular press venues [Miller, 2002; Walker, 2002; Holden, 2002; Miller, 2002; Curtis, 2003a; BDH Editor, 2003; Curtis, 2003b; Journal, 2003].

The published results above are in visualization method development, applications to remote sensing, applications to medical imaging, applications to arterial hemodynamics, applications to archaeological analysis, methodology for and comparison of effectiveness of visualization environments, and methodology for and comparison of effectiveness of visualization methods. Our progress has closely tracked the proposed deliverables; we were even able to complete several items that had been trimmed due to reductions in the original proposed budget.

Beyond publications, we have also trained more than a dozen graduate students and more than a dozen undergraduate students in how to carry out interdisciplinary research. This training has been through visualization classes involving collaborative projects and through research projects in various labs funded by this grant. Several of the students have gone on to top tier graduate programs, to academic appointments, or to excellent industry and government lab positions. We have also trained a cohort of eight design students to better understand the issues surrounding visual design for science. There is insufficient space to detail all of our results here, but we will give some examples of results relevant to the current proposal. All publications are cited above.

Visualization Synthesis and Training. In the prototype design class students developed a number of new visualization ideas for arterial blood flow. Two other visualization applications were developed for arterial flow and a third for arterial and bat-related flows. These applications will be the basis for upcoming classes. We have also created a series of visualization prototypes that borrow textures and colors from art reproductions, capturing, in many cases, the style of the piece of art. We will build on all of this work, utilizing the students that we have trained to design and implement, training more students in a course built from the prototype course, evaluating the visualization software we have developed, and using it as a base for creating new visualization methods.

Visualization Evaluation. We have conducted a number of studies to evaluate visualization methods and environments. In one we demonstrated a preference for desktop VR over a Cave for a biomedical application. In another we compared six different 2D vector visualization methods. In a third we established a relationship between quantitative user studies and subjective evaluation by visual design experts. All of the studies developed methodology that is new to scientific visualization and will help provide a base for our current proposal. The designer study paves the way for the proposed evaluation framework and for the automatic optimization of visualization methods. The other studies will be models for more traditional evaluations that we propose.

Simulation and Visualization of Arterial Hemodynamics. We have computed a range of pulsatile flows in branched tubes, as representative especially of the left-main, left-circumflex, and left anterior-descending coronary arteries, including the curvature of their axes due to their laying over the outer surface of the heart. We used straight-axis cases to compare with the results of physical flow visualization [Richardson and Christo, 1990] regarding initiation of flow separation opposite a side-branch, finding good agreement. We have formed a collaboration with Prof. Zohar Yosibash to extend computations of flow to include interactions with vessel walls with realistic compliance to achieve fuller representation of this aspect. We have begun a sub-project on the formation of thrombus [Pivkin et al., 2003a], evoking considerable interest because of desires to predict thrombus-forming potential in various common blood-handling artificial organs.

Swartz. IBN-9876543: Aerodynamics, wing biomechanics, the evolutionary diversification of the Chiroptera. Award period: 4/1/99-3/31/02, extended to 3/31/03; $434,000

Resulting publications: [Swartz, 1998; Watts et al., 2001; Swartz et al., 2003, 2004; Skene and Swartz, 2004; Swartz and Gilbert, 2004; Swartz, 2004; Fischer and Swartz, 2004; Huber and Swartz, 2004].

Our lab has worked to understand the morphological basis of flight in bats by integrating morphological, materials, and functional analyses. These analyses demonstrate that the tissues of bat wings are unique within animals.

Morphologically, the greatly elongated wing bones vary from wide and thin-walled to narrow and virtually solid, and are far more tapered distally than those of other vertebrates. Mechanically, the steep gradient in wing bone mineral content, coupled with patterned variation in cross-sectional geometry, results in bones that are strong and stiff near the shoulder but are extremely flexible in the handwing. Our mechanical tests also reveal a complex, non-linear relationship between bone mineralization and mechanical properties. Wing structure also influences flight energetics, minimizing inertial power. We have extended flight analysis recently by collecting multi-camera, high-speed digital video of bats flying in wind tunnels to create detailed 3D reconstructions of wing movements; our work comprises the largest collection of footage of flying bats yet collected, and is freely available to other investigators. We have integrated mechanical properties, structural design, and kinematic information to develop and rigorously validate an aerodynamically realistic quasi-steady computer model of bat flight based on the grey-headed flying fox, Pteropus poliocephalus.

Although our recent kinematic studies were initiated to extend our bat flight model, all of our analyses to date show complexities that challenge present understanding of bat flight. For example, we show that most bat wing bones undergo large deformations during flight and that wing angle of attack and changes continuously throughout the wingbeat, and is negative or far beyond putative stall angles during much of the lift-generating downstroke. We find that camber is larger than previously described, and tremendously variable. Together these characteristics indicate conventional understanding of bat aerodynamics is severely lacking, and highlight the need the analysis of the complex and unsteady flows around bat wings.

Students have been instrumental in all parts of this research, and we have trained post-docs, graduate students, undergraduates, and both high school students and teachers. Undergraduates have played a particularly significant role, and our labs are deeply committed to collaborative work with undergraduate co-authors, even when these efforts substantially slow the rate of publication. This research has also contributed greatly to the development of four new interdisciplinary science courses enrolling more than 80 students/year. We have also begun to communicate our work to audiences outside of academia: for example, our lab website includes material about bats, flight, and biomechanics that is suitable for the lay reader and for high school level science courses. This research was recently featured in Natural History magazine, and an soon to be released documentary on Leonardo DaVinci and bat flight produced by Gédeon Programmes and the BBC.

Lauder. Functional morphology of aquatic locomotion in fishes: function of median fins; 1998 - 2002, NSF IBN-9807012, $300,000. Experimental hydrodynamics and evolution: function of median fins in fishes; 06/01/03 - 06/01/06, NSF IBN 0316675, $426,429.

Resulting publications: [Lauder, 2000b,a; Nauen and Lauder, 2000; Wilga and Lauder, 2000; Drucker and Lauder, 2000; Liao and Lauder, 2000; Drucker and Lauder, 2001b; Nauen and Lauder, 2001a; Ferry-Graham and Lauder, 2001; Nauen and Lauder, 2001b; Lauder, 2001; Wilga and Lauder, 2001; Drucker and Lauder, 2001a; Nauen and Lauder, 2002a; Wilga and Lauder, 2002; Drucker and Lauder, 2002b; Tytell and Lauder, 2002; Nauen and Lauder, 2002b; Lauder and Drucker, 2002; Lauder, 2002; Lauder et al., 2002a; Drucker and Lauder, 2002a; Lauder et al., 2002b; Drucker and Lauder, 2003; Liao et al., 2003a; Ferry-Graham et al., 2003; Liao et al., 2003b].

During the past four years, my laboratory has focused on conducting experimental hydrodynamic analyses of fish locomotion with the aim of understanding the biomechanics of propulsion.

To accomplish these aims we have modified a technique from experimental fluid mechanics, Digital Particle Image Velocimetry (DPIV), for the study of locomotion in freely-swimming fishes. This approach has been very productive and has allowed us to integrate more traditional techniques for the study of organismic function (such as electromyography and high-speed video) with experimental fluid dynamic measurement of fin forces and the directions of force application to the water. Details of this approach have been published in number of recent papers from my laboratory (see list above).

To develop a 3D reconstruction of fin wake flow we optically reorient the laser light sheet into two or three orthogonal orientations to image flow in perpendicular planar sections of the wake. By inducing fish to swim in a highly steady manner with little variation in position or among fin beats, we have been able to reconstruct successfully 3D fin wake flow patterns during both maneuvering and steady swimming and to calculate force components for these behaviors.

By modifying techniques from experimental fluid mechanics and using these in combination with analyses of fin and body movement patterns, we have been able to test a wide variety of hypotheses concerning the function and evolution of fins in fishes.

5 Coordination Plan

While our collaborative effort is broad, spanning nine independent investigators, we believe that there are a number of reasons that it is likely to be successful.

- The proposed work of each investigator directly advances his or her own research agenda; in our experience, this is the most effective predictor of the success of such a collaborative effort.
- All investigators are leaders in their fields, with track records of successfully advancing their research agendas.
- The PI has developed many successful collaborations among biologists, medical researchers, engineers, social scientists, and artists.
- Most of the needed collaborations have already been active, some for several years – Swartz, Breuer, Karniadakis, and Laidlaw have been measuring, simulating, and visualizing airflow around bats; Lauder and Swartz have been working toward DPIV measurements for bats and fish; Laidlaw, Tarr, and Warren have been developing new evaluation strategies for visualization methods; Laidlaw and Drury have developed and run a prototype for the proposed visualization design course; and Laidlaw, Richardson, and Karniadakis have simulated, visualized, and reported on several arterial blood flow results.
- Physical proximity will facilitate success. Eight of the investigators are in Providence at Brown University or RISD; the remaining one is at nearby Harvard.
- Several personnel will be shared across groups. For example, Lauder and Swartz will share a postdoc, who will be responsible for tasks that are common to their work, such as acquiring DPIV data, acquiring motion data, and interfacing with the other groups.
- The service-like components of the proposed work will have explicit personnel assigned. For example, a technician will execute routine simulation runs (i.e., those that do not require changes to the underlying codes), manage the data, transfer it into the visualization environment, and run the visualization software. This production work will keep the momentum of the project going while leaving graduate students free to pursue research more effectively.

We detail the roles for senior personnel below, together with the structure of the personnel reporting to them individually or as shared resources.

Roles. Computer Scientist **Laidlaw** (PI) studies computational toolbuilding in the service of science. He will coordinate all of the efforts of the proposed work with the help of a postdoc. Beyond coordination and management, Laidlaw will be responsible for the synthesis of visualization methods, the characterization and evaluation of visualization tool efficacy, and the automated optimization of visualization methods. He will manage two graduate students working on those research projects. He will also manage a 50% FTE technical staff member who will use developed tools in a production mode for application datasets; the staff member will acquire data, run simulations, manage results, and run the visualization tools. Laidlaw will co-teach, with Drury, the scientific visualization class and direct the ongoing development of new support software for the course. Laidlaw and Karniadakis will be jointly responsible for motion modeling approaches. Laidlaw will interface with all of the other participants: Karniadakis for simulation results; Breuer for physics input into the evaluation process; Tarr and Warren for perceptual psychology input into the visualization method evaluation and synthesis processes; Swartz, Lauder, and Richardson for biological input into the visualization evaluation process; and Drury for art and design input into the visualization evaluation process. Laidlaw will direct a perceptual psychology postdoc who will design and execute many of the evaluation experiments.

Applied Mathematician **Karniadakis** (Co-PI) is well known for his fluid simulation system $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$. He will be responsible for flow simulation efforts, for uncertainty modeling, for gappy data modeling, and for tools that facilitate the comparison of simulated and acquired data. He will direct two graduate students in developing and applying these tools. They will run initial simulations for each type of flow scenario, creating scripts for production simulations.

Biologists **Swartz** and **Lauder** (Co-PI's) will be responsible for carrying out biological flow-related studies of bats and fish, respectively. They will coordinate with Karniadakis and Laidlaw for simulation and visualization efforts. They will co-direct a postdoctoral fellow to accomplish these efforts.

Fluid Dynamicist **Breuer** will work with Swartz and Lauder to specify effective flow-related experiments and will advise Laidlaw's group on flow-related goals for visualization characterization and evaluation. He will direct a graduate student, who will execute flow experiments, acquiring data and analyzing it using the developed modeling and visualization tools.

Bioengineer **Richardson** (Co-PI) will be responsible for carrying out biological studies of arterial blood flow. He will coordinate with Karniadakis and Laidlaw for simulation and visualization efforts.

Perceptual Psychologists **Tarr** and **Warren** will provide expertise on perception as it applies to synthesis of visualization methods and will also help with experimental design of user studies and the automated optimization of visualization methods.

Artist and Designer **Drury** will provide art, art historic, and design input into the evaluation process. He will also co-teach the visualization design class and participate in the annual development of support software for the class.

Mechanisms. We will employ several mechanisms to ensure progress. The PI's weekly lab meeting will include all personnel from this project. Students, research staff, and postdocs will all present their progress 2-3 times each year. Senior personnel will also be invited to present. Laidlaw, with the assistance of a postdoctoral scholar, will track progress toward milestones on a quarterly basis. His emphasis will be on dependencies, making sure that groups will not be blocked by other groups. We will address issues as needed. We will also continue the frequent meetings in smaller groups to address specific deliverables such as manuscripts and presentations. These meetings, whichc have been taking place for several years, in many cases, are probably the most critical mechanism to ensure timely progress. Finally, we will hold annual summit meetings where each researcher will report on progress and problems. These will be the basis for our annual report to NSF.

Specific budget items relevant to coordination are a postdoctoral scholar and a 50% FTE technical staff member. The postdoctoral scholar will assist with overall coordination of the entire project. The staff member will handle shared data and computation support.

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Zhang, S., Curry, C. T., Morris, D. S., and Laidlaw, D. H. (2000a). Streamtubes and streamsurfaces for visualizing diffusion tensor MRI volume images. In *Visualization '00 Work in Progress*.

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Zhang, S., Demiralp, C., DaSilva, M., Keefe, D., Laidlaw, D. H., Greenberg, B. D., Basser, P. J., Pierpaoli, C., Chiocca, E., and Diesboeck, T. S. (2001a). Toward application of virtual reality to visualization of DT-MRI volumes. In *Proceedings MICCAI*.

Zhang, S., Demiralp, C., Keefe, D., DaSilva, M., Greenberg, B. D., Basser, P. J., Pierpaoli, C., Chiocca, E. A., Deisboeck, T. S., and Laidlaw, D. H. (2001b). An immersive virtual environment for DT-MRI volume visualization applications: a case study. In *Proceedings of IEEE Visualization 2001*, pages 437–440.

Zhang, S., Demiralp, C., and Laidlaw, D. H. (2003). Visualizing diffusion tensor MR images using streamtubes and streamsurfaces. *IEEE Transactions on Visualization and Computer Graphics*, 9(4):454–462.

Zhang, S., Kindlmann, G., and Laidlaw, D. H. (2004b). Diffusion tensor MRI visualization. In Johnson, C. and Hansen, C., editors, *Visualization Handbook*. In Press.

David H. Laidlaw

a. Professional Preparation

1983 Sc.B. in Computer Science, Brown U., Prov., RI, *Topology and Mechanics.* Also completed requirements for an A.B. in Mathematics.
1985 Sc.M. in Computer Science, Brown U., Prov., RI, *Rendering Parametric Surfaces.*
1992 M.S. in Computer Science, Caltech, Pasadena, CA, *Material Classification of Magnetic Resonance Volume Data.*
1995 Ph.D. in Computer Science, Caltech, Pasadena, CA, *Geometric Model Extraction from Magnetic Resonance Volume Data.*

b. Appointments

2003-present	Associate Professor, Computer Science Department, Brown University
2000-2003	Stephen Robert Assistant Professor, Computer Science Department, Brown University
1998-2000	Assistant Professor, Computer Science Department, Brown University
1996-1998	Senior Research Fellow, Division of Biology, Caltech
1989-1996	Postdoctoral Research Fellow/Research Assistant, Computer Science, Caltech
1989-1993	Consultant Stardent/Advanced Visual Systems
1986-1989	Software Engineer, Stellar Computer
1983-1985	Research Assistant, Computer Science, Brown University
1984	Consultant, Basel Institute for Immunology, Switzerland

c. Publications

(i) Five Publications Most Closely Related to Project

C. Jackson, D. Acevedo, D. H. Laidlaw, F. Drury, E.Vote, and D. Keefe. Designer-critiqued comparison of 2d vector visualization methods: A pilot study. In SIGGRAPH 2003 Sketches and Applications. IEEE, 2003.

R. Kosara, C. G. Healey, V. Interrante, D. H. Laidlaw, and C. Ware. Thoughts on user studies: Why, how, and when. Computer Graphics and Applications, July/August 2003.

C. Jackson, D. Karelitz, S. A. Cannella, and D. H. Laidlaw. The great potato search: The effects of visual context on users feature search and recognition abilities in an IVR scene. In Proceedings of IEEE Visualization, October 2002.

D. Turner, I.H. Woodhouse, and D. H. Laidlaw. A synoptic visualization of fully polarimetric SAR. In Proceedings of IEEE IGARSS, 2002.

D. H. Laidlaw, R. M. Kirby, J. S. Davidson, T. S. Miller, M. da Silva, W. H. Warren, M. Tarr, (2001). Quantitative Comparative Evaluation of 2D Vector Field Visualization Methods, Proc. IEEE Visualization.

(ii) Five Other Significant Publications

A. van Dam, D. H. Laidlaw, and R. M. Simpson (2002). Future interfaces: an IVR progress report, *Computers and Graphics*,

D. Keefe, D. Acevedo,T. Moscovich, D. H. Laidlaw, J. J. LaViola (2001). CavePainting: A Fully Immersive 3D Artistic Medium and Interactive Experience, Proc 2001 Symposium on Interactive 3D Graphics.

A. van Dam, A. S. Forsberg, J. J. LaViola, and R. M. Simpson (2000). Immersive Virtual Reality for Scientific Visualization: A Progress Report, *IEEE Computer Graphics and Applications*, 20(6) pp. 26-52.

D. H. Laidlaw (2001),Loose, artistic ``textures" for visualization. IEEE Computer Graphics and Applications, 21(2):6--9.

Upson, C., Faulhaber, T., Kamins, D., Laidlaw, D. H., Schleigel, D., Vroom, J. Gurwitz, R., and van Dam, A. (1989). The Application Visualization System: A Computational Environment for Scientific Visualization. *Computer Graphics and Applications*, 9(4).

d. Synergistic Activities

Last year a major revision of a new graduate/undergraduate class, *Interdisciplinary Scientific Visualization*, explored design issues in scientific visualization from two perspectives: illustration and computer science. The course was co-taught with Rhode Island School of Design (RISD) Illustration Department Chairman Fritz Drury. Together we worked with students from both RISD and Brown to design and realize new virtual reality interfaces for exploring 3D time-varying flow. Students learned about communicating and working with researchers across multiple fields. See course web page for more info: http://www.cs.brown.edu/courses/cs237.

Organized panel at Visualization '98 conference on Art and Visualization (best panel at conference). Participated in follow-on Visualization '99 and Visualization '01 panels. All probed issues of interdisciplinary collaborations for visualization.

Co-taught one-day course at premiere computer graphics conference, SIGGRAPH, about using art-based methods for scientific visualization. I led a two-hour session where approximately 80 computer graphics professionals used traditional art media (paint, charcoal, markers, chalk, etc.) to represent multivalued scientific data.

The final publication in c.ii. above describes AVS, a visualization software product that I was a principal developer on at Stellar Computer. It is widely used to process and visualize scientific data from many disciplines.

I have advised and continue to recruit out undergraduates for research projects both at Brown and, previously, at Caltech. Many of the projects have culminated in research publications. Several have been with women in computer science, a traditionally underrepresented group. I organize the Brown Computer Science undergraduate research opportunities web pages.

e. Collaborators and Other Affiliations

(i) Collaborators and Co-Editors: Eric T. Ahrens, Caltech, Joseph W. Asa, Matthew J. Avalos, Caltech, C. Bajaj, U. Texas, Thomas F. Banchoff, Alan H. Barr, Caltech, Celia F. Brosnan, Albert Einstein College of Medicine, Kristen L. Cook, Caltech, Joseph Crisco, Brown, Bena L. Currin, Caltech, Mary E. Dickinson, Caltech, Paul E. Dimotakis, Caltech, John Donoghue, Brown University, Kurt W. Fleischer, Pixar, Andrew S. Forsberg, Brown, Geoffrey Fox, Felice Frankel, MIT, Scott E. Fraser, Caltech, Yuri M. Goldfeld, Caltech, Galen G. Gornowicz, Dreamworks SKG, Cindy Grimm, Washington U., Donald House, Texas A\&M, Victoria Interrante, U. of Minnesota, Russell E. Jacobs, Caltech, David Kremers, Caltech,
Daniel B. Lang, Caltech, H. Marmanis, Brown, Carol Readhead, Cedars Sinai Medical Center,
Sharon Swartz, Brown, Jerome Sanes, Brown, Jerry W. Shan, Caltech, Jeffrey M. Silverman, Cedars Sinai Medical Center, Michael Tarr, Brown, J. Michael Tyszka, City of Hope Medical Center, Colin Ware, U. New Hampshire, William Warren, Brown, Iain Woodhouse, U. Edinburgh

(ii) Advisees: Daniel Acevedo-Feliz, Stuart Andrews, Cullen Jackson, Daniel Keefe, R. Michael Kirby, Georgeta Elizabeth Morai, Paul Reitsman, Eileen Vote, Song Zhang.

(iii) Advisors: Alan H. Barr, Caltech, Scott E. Fraser, Caltech.

George Em Karniadakis

a. Professional Preparation

B.Sc., NTU, Athens (Greece), 1982
M.S., MIT, 1984
Ph.D., MIT, 1987
Postdoc, Stanford University, 1987-88

b. Appointments

July 1996 - present, Professor, Applied Mathematics, Brown University.
Sept. 2000 - present, Visiting Professor, MIT (Wallace Lecturer).
Jan. 1994 - June 1996, Associate Professor, Brown University.
Spring quarter 1993: Visiting Professor, Caltech.
Sept. 1988 - Dec. 1993: Assistant Professor, Princeton University.

c. Publications

(i) Five most closely related publications.

Y. Du and G.E. Karniadakis, "Suppressing turbulence by means of a transverse traveling wave," Science, vol. 288, pp. 1230-1234, 2000.

D. Xiu and G.E. Karniadakis, "The Wiener-Askey polynomial chaos for stochastic differential equations," SIAM J. Sci. Comput., 24(2), 619-644, 2002.

J. Xu, M. Maxey and G.E. Karnidakis, "Numerical Simulation of Turbulent Drag Reduction using Micro-Bubbles," J. Fluid Mech. vol. 468, 271-281, 2002.

X. Ma, G.-S. Karamanos and G.E. Karniadakis, "Dynamics and low-dimensionality in turbulent near-wake," J. Fluid Mech., vol. 410, 29-65, 2000.

I.V. Pivkin, P.D. Richardson, D.H. Laidlaw and G.E. Karniadakis, "Combined effects of Pulsatile flow and dynamic curvature wall shear stress in a coronary artery bifurcation model," Submitted: J. Biomechanics, 2003.

(ii) Five other publications.

G.E. Karniadakis and S.J. Sherwin, "Spectral/hp Element Methods for CFD," Oxford University Press, 1999.

G.E. Karniadakis and R.M. Kirby, "Parallel Scientific Computing in C++ and MPI," Cambridge University Press, 2002.

G.E. Karniadakis and Ali Beskok, "Microflows: Fundamental and Simulation," Springer, 2001.

D. Xiu and G.E. Karniadakis, "A new stochastic approach to transient heat conduction modeling with uncertainty," International Journal of Heat and Transfer, 46, 4681-4693, 2003.

D. Lucor, D. Xiu, C.-H. Su and G.E. Karniadakis, "Predictability and Uncertainty in CFD," Int. J. Num. Meth. Fluids, 43(5), 485-505, October 20, 2003.

d. Synergistic Activities

Developed spectral/hp element methods and first algorithms for MEMS flows and published first books on these subjects.

Pioneered parallel computing in 3D turbulence simulations in the mid-eighties.

Organized several International Conferences/Symposia including the first Symposium on Wavelets & Turbulence (1991), and on Discontinuous Galerkin Methods (1999).

Developed and maintained the code NEKTAR (freeware) used in Universities, national labs, and industry.

Member of the Users Advisory Boards of NCSA and PSC and also a member of the allocations committee of NPACI. During the past two year he participated in panels and testimony for the "teragrid" and "ETF" initiative as well as the new initiative on "petaflops" systems. He also provided results of his benchmarking activities to the NSF centers.

Work appeared on the covers of many scientific journals (e.g. Physics Today, Scientific Computing & Automation, Parity (Japanese), etc.); also in SCIENCE, in Aerospace 2001 (work on uncertainty), NCSA/ACCESS (2002, SC.02 highlights), HPCwire (2003).

e. Collaborators and Other Affiliations

(i) Collaborators: C. Crysostomidis, D. Yue and M. Triantafyllou (MIT), M. Gharib (Caltech), D. Rockwell (Lehigh University), M. Maxey, C.-H. Su, D. Laidlaw, P. Richardson & A. van Dam (Brown University).
(ii) Advisors: Professors A.T. Patera and B.B. Mikic (MIT, Ph.D. thesis advisors). Professors P. Moin and J. Kim (Stanford/Nasa Ames, Post-doctoral advisors).
(iii) Graduate and Postdoctoral Advisees: Dr. P.F. Batcho (Los Alamos); Dr. R.D. Henderson (Caltech); Dr. I.G. Giannakouros (ETH, Zurich); Prof. S.J. Sherwin (Imperial College); Prof. A. Beskok (University of Texas A & M); Dr. D.J. Newman; Dr. C.H. Crawford (IBM); Dr. B. Gervang; Dr.L. Kaiktsis (ETH, Zurich); Dr. D. Pathria; Dr. D. Sidilkover (ICASE); Dr. C. Quillen; Dr. T. Matushima; Dr. Ma Xia (Brown University); Prof. T. Warburton (University of New Mexico); Dr. J. Trujillo; Dr. I. Lomtev (J.P. Morgan); Dr. C. Evangelinos (MIT); Dr. H. Marmanis; Dr. Y. Du (Microsoft); Prof. F. Liu (University, Taiwan), Prof. R.M. Kirby (U. Utah); Dr. D. Lucor (MIT)

Peter Damian RICHARDSON

a. Professional Preparation

Undergraduate Institution: City & Guilds College of the Imperial College of Science, Technology and Medicine, of the University of London, Major: Mechanical Engineering
B.Sc.(Eng.) with honours, A.C.G.I. 1955

Graduate Institution: Imperial College of Science, Technology and Medicine, of the University of London, Major: Mechanical Engineering
Ph.D., D.I.C. 1958

Postdoctoral: In my country of origin one can take Higher Doctorates based on examination of published works and subject to University Regulations, candidacy being restricted by earlier degrees; I have successfully completed two of these at the University of London:
D.Sc.(Eng.) in Mechanical Engineering 1974
D.Sc. in Applied Physiology 1983

b. Appointments:

1984 - present Professor of Engineering and Physiology, Brown University, Providence RI
1968 - 1984 Professor of Engineering, Brown University
1965 - 1968 Associate Professor of Engineering, Brown University
1960 - 1965 Assistant Professor of Engineering, Brown University
1959 - 1960 Research Associate, Brown University, Providence RI
1958 - 1959 Visiting Lecturer, Brown University, Providence RI
1955 - 1958 Demonstrator, Department of Mechanical Engineering, City & Guilds College of Imperial College of Science, Technology and Medicine, London, UK

c. Publications

(i) Five most closely related to proposed project.

Guo D, Richardson PD. Automatic vessel extraction from angiogram images. IEEE Computers in Cardiology l25: 441-444, 1998.

Richardson PD. Biomechanics of plaque rupture: progress, problems and new frontiers. Ann Biomed Engng 30: 524-536, 2002

Sobel JA, Forsberg A, Richardson PD, Laidlaw DH, Keefe DF, Pivkin I, Karniadakis GE. Arterial flows seen in virtual reality. Biomedical Engineering: Recent Developments, Vossoughi J (ed). Proceedings 21st Southern Biomedical Engineering Conference, Sept 2002, pp.349-350. Biomed Res Foundation, Olney MD, 2002. ISBN 1-930636-01-6

Richardson PD. Elliptic delamination as an early stage in atherosclerotic plaque evolution: Fluid mechanical aspects. Biorheology 40: 417-421, 2003.

Forsberg A, Laidlaw D, Sobel JS, Zelenik R, Keefe D, Richardson PD, Karniadakis GE, Pivkin I. Particle flurries: A case study of synoptic 3D pulsatile flow visualization. Accepted for IEEE Computer Graphics and Applications, Sept 2003

(ii) Five other significant publications.

Davies MJ, Richardson PD, Woolf N, Katz DR, Mann J. "Risk of thrombosis in human atherosclerotic plaques: role of extracellular lipid, macrophage, and smooth muscle cell content" Brit Heart Jl 69:377-381, 1993

Lendon CL, Davies MJ, Richardson PD, Born GVR. "Testing of small connective tissue specimens for the determination of the mechanical behavior of atherosclerotic plaques" Jl Biomed Engng 15: 27-33, 1993

Davies MJ, Woolf N, Rowles P, Richardson PD. "Lipid and cellular constituents of unstable human aortic plaques." Basic Res in Cardiology 89: 33-39, Suppl 1, 1994

Davies MJ, Treasure T, Richardson PD. "The pathogenesis of spontaneous arterial dissection." Heart 75: 434-435, 1996.

Richardson PD. "Flows and Wall Mechanics in Critical Arteries", Japan Society of Mechanical Engineers, Centennial Grand Congress, Proceedings of the International Conference on New Frontiers in Biomechanical Engineering (Tanishita K, Sato M, eds), 23-25, July 1997.

d. Synergistic Activities

When active in research on artificial internal organs, I not only published many papers on them but also partook in the inception of a standards committee for blood oxygenators, first in ASAIO the professional society and remained a member after it was transferred to AAMI (American Institute for Medical Instrumentation) for many years, thereby helping the research influence standards for commercial practice.

Having performed research related to development of bioresorbable vascular grafts I realized there were significant problems in diseased arteries which could be tackled with our methods and established collaborations with top clinical researchers, leading to well-received papers in The Lancet, British Heart Journal, etc.

Following interaction with a sabbatical visitor, I wrote a paper in the Journal of Sedimentary Geology. With advances in underwater scanning technology, this turned out to be relevant to interpreting paleo-scour on seabeds at ancient shipwrecks (e.g. Henry VIII's flagship Mary Rose), and I am following this up.

e. Collaborators

(i) Forsberg A, Keefe DF, Karniadakis GE, Laidlaw DH, Pivkin IV, Sobel JA, Zelenik R, all at Brown University
(ii) Prof Sir Owen Saunders FRS (deceased) PhD thesis advisor, Profs J. Kestin, H. Sogin (both deceased) post-doc sponsors
(iii) Dongbai Guo, PhD, Oracle Corp

Sharon Miriam Swartz

a. Professional Preparation

1977-1981	B.A.	Oberlin College. Biology and Sociology/Anthropology, with High Honors
1982-1985	M.S.	The University of Chicago. Evolutionary Biology
1985-1988	Ph.D.	The University of Chicago. Evolutionary Biology

b. Appointments

1996-present	Associate Professor, Brown University, Department of Ecology and Evolutionary Biology Adjunct Associate Professor, Division of Engineering
February–July, 1996	Parental Leave
1990-1996	Assistant Professor, Brown University, Department of Ecology and Evolutionary Biology Adjunct Assistant Professor, Division of Engineering
April–August, 1993	Parental Leave
1987-1990	Assistant Professor, Northwestern University Medical School, Department of Cell Biology & Anatomy; & Northwestern University College of Arts and Sciences, Department of Anthropology

c. Publications

(i) Five most closely related to the proposed project.

Swartz, S. M., K. L. Bishop and M. F. Ismael-Aguirre. In press. Dynamic complexity of wing form in bats: implications for flight performance. In Functional and Evolutionary Ecology of Bats (Z. Akbar, G. McCracken, & T. H. Kunz, eds.). Oxford University Press.

Swartz, S. M., P. W. Freeman, and E. F. Stockwell. 2003. Ecomorphology. in Bat Ecology. (T. H. Kunz, ed.) pp. 257-300. The University of Chicago Press.

Watts, P., Mitchell, E. J., and S. M. Swartz. 2001. A computational model for estimating mechanics of horizontal flapping flight in bats: Model description and comparison with experimental results. Journal of Experimental Biology 246:1-32.

Swartz, S. M., M. D. Groves, H. D. Kim and W. R. Walsh. 1996. Mechanical properties of bat wing membrane skin: aerodynamic and mechanical functions. Journal of Zoology, London 239:357-378.

Swartz. S. M., M. B. Bennett, and D. R. Carrier. 1992. Wing bone stresses in free flying bats and the evolution of skeletal design for flight. Nature 359:726-729.

(ii) Five other publications.

Swartz, S. M., A. A. Biewener, and J. E. A. Bertram. 1989. Telemetered in vivo strain analysis of locomotor mechanics of brachiating gibbons. Nature 342:270-272.

Bertram, J. E. A. and S. M. Swartz. 1991. The "Law of bone transformation": A case of crying Wolff? Biol. Rev. 22:245-273.

Swartz, S. M. 1997. Allometric patterning in the limb skeleton of bats: Implications for the mechanics and energetics of powered flight. Journal of Morphology 234:277-294.

Swartz, S. M., A. Parker, and C. Huo. 1997. Theoretical and empirical scaling patterns and topological homology in bone trabeculae. Journal of Experimental Biology 201:573-590.

Swartz. S. M. 1998. Skin and bones: the mechanical properties of bat wing tissues. in Bats: Phylogeny, Morphology, Echolocation, and Conservation Biology. (T. H. Kunz and P. A. Racey, eds.) pp. 109-206. Smithsonian Institution Press.

d. Synergistic Activities

Brown University's representative for Project Kaleidoscope Faculty for the 21st Century network. PKAL is a national organization devoted to building and connecting leaders shaping the future of undergraduate studies of science, mathematics, engineering and technology at the university level. As one of 100 F21 representatives for the 2001/2 academic year, I participated in an alliance of scientists and institutions working to transform the learning environment for undergraduate students in SME&T by building institutional teams with a driving vision of what works and who are committed to action. Through PKAL, I work to foster public understanding of how a strong undergraduate science community serves the national interest.

For the past nine years, I have served as the biological sciences representative to Brown University's Undergraduate Research and Teaching Assistantships program. Through this program, we stimulate student-faculty collaboration in both scholarly research and course development; , I have help to select over 1400 such projects. I have sponsored over 45 undergraduate research projects in my lab, and have 8 undergraduates as coauthors on significant scientific publications. I have been responsible for the development of the first Team UTRA Grants, designed to extend hands-on research experiences to larger teams of students, thereby enriching and facilitating the way students become immersed in research and offering such opportunities to many more students than is possible in solely one student/one teacher projects.

Brown's Women in Science and Engineering (WiSE) program provides diverse support and mentorship opportunities to undergraduates with interests in SME&T. I have worked actively with this group as a Steering Committee member and as an Affinity Group Leader. In the Affinity Group program, in particular, I have the opportunity to serve as a mentor to women with career interests in biology, and to provide ongoing academic advice, career counseling, and support, with special attention to the needs and issues of women in fields in which they have been traditionally underrepresented.

Along with ten faculty from diverse science departments at Brown, I am part of a working group to develop more effective techniques to teach fundamental, core scientific concepts that recur throughout university level science education. To this end, we received a grant from the NSF CCLI Program, Context-Rich Interactive Science Teaching and Learning System (CRISTALS) to develop prototype multi-level, multidisciplinary web-based teaching modules.

e. Collaborators and Other Affiliations

(i): Collaborators: Dr Janet Blume, Brown University; Dr. Patricia Freeman, University of Nebraska; Dr. Les Hall, The University of Queensland; Dr. John Skedros, University of Utah.

(ii): Graduate Advisors: Dr. Andrew A. Biewener, Harvard University; Dr. Russell H. Tuttle, The University of Chicago; No postdoctoral advisor

(iii): Thesis Advisor and Postgraduate-Scholar Sponsor: past thesis advisees: Dr. Jennifer Chickering; Dr. Kathleen Earls; present: Kristin Bishop, José Iriarte-Diaz

(iv): Postdoctoral advisees: Dr. Gregory Erickson, Dr. Kevin Middleon, Dr. Katherine Rafferty; Dr. Elizabeth Stockwell, Dr. Philip Watts

Kenneth Breuer

a. Professional Preparation

- ScB. Brown University, Providence RI. Division of Engineering. Summa cum Laude (with Honors). Concentration in Fluids and Thermal Sciences. June 1982.
- M.S. Massachusetts Institute of Technology. Cambridge MA. Department of Aeronautics and Astronautics. September 1984.
- Ph.D. Massachusetts Institute of Technology. Cambridge MA. Department of Aeronautics and Astronautics. June 1998.
- Post-Doctoral Research Fellow. Brown University, Providence RI, Division of Applied Mathematics. September 1988 . August 1990.

b. Appointments

- September 1999 - Present. Associate Professor of Engineering, Brown University, Providence RI
- September 1998 - September 1999. Principal Research Scientist, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA
- September 1996 - September 1998. Harold and Esther Associate Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology
- September 1990 - September 1996. Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

c. Publications

(i) Five most closely related publications.

Jin, S., Huang, P., Park, J., You, J. Y., & Breuer, K. S. "Near-wall PTV measurements using evanescent wave illumination". PIV '03 Paper 3237. Proceedings 5th International Symposium on PIV. Busan, Korea. Sep, 2003.

Kim, M-J. and Breuer, K.S. "Enhanced Diffusion due to Bacterial Motion". IMECE2003-44014. In Proceedings of ASME-IMECE. Washington DC, November 2003. (in review, *Phys Rev Lett*.)

A Gallery of Fluid Motion. M. Saminy, K. Breuer, G. Leal and P. Steen Cambridge University Press, January 2004.

*MultiMedia Fluid Mechanics (*CD-Rom). G. Homsy, H. Aref, K. Breuer, S. Hochgreb, B. Munson, K. Powell C. Robertson. Cambridge University Press, January 2000.

Jin, S., Huang, P, Park, J. and Breuer, K.S. "Near-Surface Velocimetry using Evanescent Wave Illumination". IMECE2003-44015. In Proceedings of ASME-IMECE. Washington DC, November 2003 (accepted for publication in *Experiments in Fluids*)

(ii) Five other publications.

Kim, M. J., Kim, M. J., Bird, J. C., Park, J., Powers, T. R., & Breuer, K. S. "Macro-scale PIV Experiments on Bacterial Flagellar Bundling". PIV '03 Paper 0085. *Proceedings, 5th International Symposium on PIV*, Busan, Korea. Sep, 2003Westin, K.J.A, Choi, C-H, and Breuer, K.S. A novel system for measuring liquid flow rates with nanoliter per minute resolution *Experiments in Fluids* 34, 2003. pp 635—642..

Han, G, Bird, J.C., Westin, KJ & Breuer, K.S. “Infrared Diagnostics for the measurement of fluid and solid motion inside MEMS”. *Microscale Thermophysical Engineering (in press)* 2004.

Choi, C-H, Westin, K.J.A, and Breuer, K.S. Apparent Slip in Hydrophilic and Hydrophobic Microchannels *Physics of Fluids* October 2003

Arklic, E.B., Schmidt, M.A. & Breuer, K.S. “Slip flows and Tangential Momentum Accommodation in Micromachined Channels.” *J. Fluid Mech*. **437** pp. 29-43. June, 2001.

Breuer, K.S. “Lubrication in MEMS”, in the CRC Handbook of MEMS, Ed. M Gad-el-Hak. CRC Press. (2001)

d. Synergistic Activities

Active Research Programs: Microscale fluid mechanics, Biofluid properties, Bacterial Mechanics, Active control of Turbulence, Bat flight mechanics. Research Group 2 Post Docs, 5 grad students 4 undergrad students.

Founder and Chair ASME *Microfluidics Symposium* 2000, 2001 and Vice Chair of *ASME Micro and Nanofluidics Technical Committee*.

Editor: *Microscale Diagnostics* (Springer 2003)

Director of Graduate Programs: Oversee graduate programs in the Division of Engineering at *Brown University*.

New Course Development: Developed new course on Microelectromechanical Systems (MEMS), an interdisciplinary course on materials designed for advanced undergraduates and graduate students.

e. Collaborators & Other Affiliations

(i) Collaborators: Alan Epstein (*MIT*), Martin Schmidt (*MIT*), Steven Senturia (*MIT*), George Homsy (*University of California-Santa Barbara*), Howard Berg (Harvard), Linda Turner (Harvard) Greg Huber (UMass) Thomas Powers (Brown).
(ii) Graduate and Post Doctoral Advisors: Marten Landahl (*Deceased*), Sheila Widnall (*MIT*), Joseph Haritonidis (The *Ohio State University*), Lawrence Sirovich (*Mt. Sinai School of Medicine*)
(iii) Thesis Advisor and Postgraduate-Scholar Sponsor*: M.S.*: Chang-Hwan Choi, Peter Huang, Jorge Carretero, Nicholas Savoulides (*MIT*) Eugene Kang (*Mindspring*), Peter Kwok (*US DoT*) *Ph.D.:* Errol Arkilic (*Redwood Microsystems*), Aravind Padmanabhan (*Honeywell*), Ruben Rathnasingham (*University of Michigan*), Edward Piekos (Sandia); Doyle Orr (*Iomega Inc*), Rudolph King (*NASA Langley*), Robert Bayt (*United Technologies Research Center*). Jinwoo Bae (*Samsung*) *Postdoc:* Michael Muller, (*Brown*) Johan Westin (*KTH, Sweden*), Jinil Park (*Brown*), Gengxin Han (*University of Arizona*), Mark Sheplak (*University of Florida*). Anju Nayaar. (Total theses supervised since 1990: 15 MS, 9 Ph.D.)

Fritz Drury

a. Professional Preparation

BA 1977 Stanford University
MFA 1981 Yale University School of Art

b. Appointments

Rhode Island School of Design, Providence RI
Professor of Illustration, June 2003-present
Department Head, Illustration 2000-2003
Associate Professor of Illustration and Foundation Studies, 1997-2003.
Adjunct Professor of Illustration and Painting 1981-1997.

c. Publications

Drawing Structure and Vision , textbook on drawing technique and tradition, Fritz Drury and Joanne Stryker, anticipated publication, September 2004, Prentice Hall, Upper Saddle River NJ.
Applying the Lessons of Visual Art to the Study of the Brain: abstract for presentation at Winter Conference on Brain Research, January 2004, with Profs David Laidlaw, David Kremers, Russell Jacobs, Arthur Toga.
Designer-critiqued Comparison Of 2D Vector Visualization Methods: A pilot study. In SIGGRAPH 2003 Sketches and Applications. IEEE, 2003. Cullen Jackson, Daniel Acevedo, David H. Laidlaw, Fritz Drury, Eileen Vote, and Daniel Keefe.
New Paintings, Project Room, The Painting Center, NYC October 2002
177th Annual Invitational, National Academy of Design, NYC May 2002
Solo Show, AAA Gallery, NYC, November 1998.
Review in Art in America July 1999, by Nancy Grimes.
Solo Show, "Bedtime Stories", Nancy Moore Gallery, NYC, May, 1997.
Solo Show, Black and Greenberg Gallery, NYC, April 1995.
Solo Show, "Nature", 55 Mercer Gallery, NYC, October 1993.
Review in Art in America, June 1994, by Eleanor Heartney.

d. Synergistic Activities

January 2004, Presentation at Winter Conference on Brain Research, Natural Media and Artistic Process in Scientific Visualization (within the group presentation: Applying Lessons of Visual Art to the study of the Brain).

March-May 2003- advisor to study by Daniel Acevedo and Colin Jackson on the design Visualization icons in relation to perceptual psychology.

September-December 2002, co-taught Interdisciplinary Scientific Visualization at Brown University with Professor David Laidlaw, studying collaboration between artists and scientists in the design of immersive, interactive scientific visualizations.

January- May 2003-Participant in interdisciplinary discussions between Brown University scientists and artists and designers from Rhode Island School of Design on the feasibility of collaborative work on visualization projects.

e. Collaborators and Other Affiliations

(i) Collaborators: Professor David Laidlaw, Department of Computer Science, Brown University, Professor Peter Richardson, Department of Engineering, Brown University, Professor Russell E. Jacobs, California Institute of Technology, Professor Arthur Toga, UCLA School of Medicine, David Kremers, California Institute of Technology, Department of Biology, Artist in Residence, Daniel Keefe, Department of Computer Science, Brown University, Daniel Acevedo, Department of Computer Science, Brown University, Cullen Jackson, Department of Computer Science, Brown University

(ii) Graduate Advisors: Professor William Bailey (emeritus) Yale School of Art, Professor Bernard Chaet (emeritus) Yale School of Art

George V. Lauder

a. Professional Preparation

Undergraduate: Harvard University, Cambridge, MA.	A.B. (Biology) 1976.
Graduate: Harvard University, Cambridge, MA.	M.A. (Biology)1978.
Graduate: Harvard University, Cambridge, MA.	Ph.D. (Biology) 1979.
Postdoctoral: Harvard University, Cambridge, MA	1979-1980

b. Appointments

1999 – present. Professor of Organismic and Evolutionary Biology,Harvard University.
1990 - 1999. Professor of Ecology and Evolutionary Biology, University of California, Irvine.
1986 - 1990. Associate Professor, University of California, Irvine.
1981 - 1986. Assistant and Associate Professor of Anatomy, The College,
and the Committee on Evolutionary Biology, University of Chicago.

c. Publications

(i) Five publications most closely related to project.

Drucker, E. G. and G. V. Lauder. (1999). Locomotor forces on a swimming fish: three-dimensional vortex wake dynamics quantified using digital particle image velocimetry. J. Exp. Biol. 202: 2393-2412.

Drucker, E. G. and G. V. Lauder. (2000). A hydrodynamic analysis of fish swimming speed: wake structure and locomotor force in slow and fast labriform swimmers. J. Exp. Biol. 203: 2379-2393.

Lauder, G. V. (2000). Function of the caudal fin during locomotion in fishes: kinematics, flow visualization, and evolutionary patterns. *Amer. Zool*. 40: 101-122.

Wilga, C. D. and G. V. Lauder. (2002) Function of the heterocercal tail in sharks: quantitative wake dynamics during steady horizontal swimming and vertical maneuvering. J. Exp. Biol. 205: 2365-2374.

Drucker, E. G. and G. V. Lauder. (2002) Experimental hydrodynamics of fish locomotion: functional insights from wake visualization. Integ. Comp. Biol. 42: 243-257.

(ii) Five other publications.

Lauder, G. V. (1994). Homology, form, and function. In *Homology: the Hierarchical Basis of Comparative Biology* (ed. B. Hall), pp. 151-196. New York: Academic Press.

Lauder, G. V. (1996). The argument from design. In *Adaptation* (ed. M. R. Rose and G. V. Lauder), pp. 55-91. San Diego: Academic Press.

Lauder, G. V. (2000). Biomechanics and behavior: analyzing the mechanistic basis of movement from an evolutionary perspective. In *Biomechanics in Animal Behavior* (ed. P. Domenici and R. W. Blake), pp. 19-32. Oxford: BIOS Scientific.

Drucker, E.G. and Lauder, G.V. (2001) Locomotor function of the dorsal fin in teleost fishes: experimental analysis of wake forces in sunfish. J. Exp. Biol. 204: 2943-2958.

Liao, J. C., D. N. Beal, G. V. Lauder, M. S. Triantafyllou. 2003. Fish exploiting vortices decrease muscle activity. Science 302: 1566-1569 (Also see cover photograph and accompanying Perspective article).

d. Synergistic Activities

Adapting flow visualization technique (DPIV) from field of fluid engineering for use in studies of form and function in freely-moving organisms. Articles about this approach have appeared in industry trade journals.

Advisor on American Museum of Natural History's new Hall of Ocean Life. Provided advice on three display panels showing presenting the physiology of feeding, respiration and locomotion in fishes.

Editorial Board, Journal of Experimental Biology, Journal of Morphology, Physiological and Biochemical Zoology.

e. Collaborators and Other Affiliations

(i) Collaborators: David Beal (MIT), Andrew Biewener (Harvard Univ.), Rick Blob (Clemson Univ.), Kathy Dickson (Cal. State Fullerton), Eliot Drucker (Harvard Univ.), Lara Ferry-Graham (U.C. Davis), Ellen Freund (Harvard Univ.), Alice Gibb (Northern Arizona Univ.), Gary Gillis (Mt. Holyoke College), S. Tonia Hsieh,(Harvard. Univ.), James Liao (Harvard Univ.), Peter Madden (Harvard), Rajat Mittal (George Washington Univ.), Jennifer Nauen (Harvard Univ.), Matt McHenry (Harvard Univ.), Bob Shadwick (Univ. of California, San Diego), Sharon Swartz (Brown Univ.), Michael Triantafyllou (MIT), Eric Tytell (Harvard Univ.), Peter Wainwright (Univ. of California, Davis), Jeff Walker (Univ. of Southern Maine), Cheryl Wilga (Univ. Rhode Island).

(ii) Graduate Advisees: (12 total): Past: Dr. Brian Clark, Dr. Peter Wainwright, Dr. Margaret Rubega, Dr. Miriam Ashley-Ross, Dr. Alice Gibb, Dr. Amy Cook, Dr. Gary Gillis, Dr. Lara Ferry-Graham, Erin Schmidt (Master's student.). Current: (all Ph.D. candidates): Jimmy Liao, Tonia Hsieh, Eric Tytell, Em Standen, Chris Richards. Postdoctoral students advised (9 total): Past: Dr. William Bemis, Dr. Julian Humphries, Dr. Chris Sanford, Dr. Steve Reilly, Dr. Bruce Jayne , Dr. Cheryl Wilga. Current: Dr. Eliot Drucker, Dr. Jen Nauen, Dr. Matt McHenry, Dr. Peter Madden.

(iii) Graduate advisor: Dr. Karel F. Liem, Harvard University.

MICHAEL J. TARR

a. Professional Preparation

Cornell University Psychology B.A. 1984
Massachusetts Institute of Technology Brain and Cognitive Sciences Ph.D. 1989

b. Appointments

2002-2003 *Interim Executive Director*, Brain Science Program, Brown University
2001-2002 *Associate Chair*, Department of Cognitive and Linguistic Sciences, Brown University
2001-present *Fox Professor of Ophthalmology and Visual Sciences*, Brown University
2000-present *Professor* of Cognitive and Linguistic Sciences, Brown University
1997-2000 *Associate Professor* of Cognitive and Linguistic Sciences, Brown University
1995-1997 *Assistant Professor* of Cognitive and Linguistic Sciences, Brown University
1991-1995 *Assistant Professor* of Psychology and Computer Science, Yale University
1993-1996 *Visiting Scientist*, Max-Planck Institut, Tübingen, Germany
1991 *Visiting Scientist*, University of Pennsylvania GRASP Laboratory
1989-1991 *Assistant Professor* of Psychology, Yale University

c. Publications

(i) Five publications most closely related to the proposal.

Tarr, M. J., & Cheng, Y. D. (2003). Learning to see faces and objects. *TRENDS in Cognitive Sciences*, *7*(1), 23-30. [Cover Article]

Tarr, M. J. (2003). Visual Object Recognition: Can a Single Mechanism Suffice? In M. A. Peterson & G. Rhodes (Eds.), *Perception of Faces, Objects, and Scenes: Analytic and Holistic Processes* (pp. 177-211). Oxford, UK: Oxford University Press.

Tarr, M. J., & Gauthier, I. (2000). FFA: A Flexible Fusiform Area for subordinate-level visual processing automatized by expertise. *Nature Neuroscience*, *3* (8), 764-769.

Gauthier, I., Tarr, M. J., Moylan, J., Anderson, A. W., Skudlarski, P., & Gore, J. C. (2000). The fusiform "face area" is part of a network that processes faces at the individual level. *Journal of Cognitive Neuroscience, 12*, 495-504.

Gauthier, I., & Tarr, M. J. (2002). Unraveling mechanisms for expert object recognition: Bridging brain activity and behavior. *Journal of Experimental Psychology: Human Perception and Performance*, *28* (2), 431-446.

(ii) Five other publications.

Tarr, M. J., & Kriegman, D. J. (2001). What defines a view? *Vision Research, 41*(15), 1981-2004.

Gauthier, I., Behrmann, M., & Tarr, M. J. (1999). Can face recognition really be dissociated from object recognition? *Journal of Cognitive Neuroscience*, *11* (4), 349-370.

Gauthier, I., Tarr, M. J., Anderson, A. W., Skudlarski, P., & Gore, J. C. (1999). Activation of the middle fusiform "face area" increases with expertise in recognizing novel objects. *Nature Neuroscience*, *2*(6), 568-573.

Tarr, M. J., Williams, P., Hayward, W. G., & Gauthier, I. (1998). Three-dimensional object recognition is viewpoint-dependent. *Nature Neuroscience*, *1* (4), 275-277.

Tarr, M. J., & Bülthoff, H. H. (1998). Image-based object recognition in man, monkey, and machine. *Cognition*, *Special Issue on Image-based Object Recognition* (Tarr & Bülthoff, eds.)*, 67*, 1-20.

d. Synergistic Activities

Developed extensive collection of both familiar and novel 3D objects that are distributed through the web (http://www.tarrlab.org/).

Collaborated on the development of software ("RSVP") for running behavioral studies on the Apple Macintosh. This software is freely distributed on the web (http://psych.umb.edu/rsvp/) and is used in many laboratories around the world.

Founded and helped developed the Pre-Psychonomics Workshop on Object Perception and Memory (OPAM) – now in its 11th year and with well over 100 participants annually.

e. Collaborators & Other Affiliations

(i) Collaborators: James Anderson, Brown University; Marlene Behrmann Carnegie Mellon University; Peter Belhumeur, Columbia University; Daniel Bub, University of Victoria, CANADA; Heinrich Bülthoff, Max-Planck Institute, Tübingen, GERMANY; Gary Cottrell, UCSD; Tim Curran, University of Colorado; Leslie Kaelbling, M.I.T.; Daniel Kersten, University of Minnesota; David Kriegman, University of Illinois; Michael Paradiso, Brown University; Jerome Sanes, Brown University; Robert Schultz, Yale University; David Sheinberg, Brown University; James Tanaka, Oberlin College; William Warren, Brown University; Alan Yuille, Smith-Kettlewell Eye Institute
(ii) Graduate Advisor: Steven Pinker M.I.T.
(iii) Primary Thesis Advisor and Postgraduate-Scholar Sponsor: Aginsky, Vlada Microsoft Corp., Redmond, WA, Ashworth, Alan Brooks AFB, Texas
Cutzu, Florin Indiana University, Gauthier, Isabel Vanderbilt University, Hayward, William Chinese University of Hong Kong, Jackson, Cullen Brown University
Naor, Galit Brown University, Rossion, Bruno Université Catholique de Louvain, BELGIUM, Vuong, Quoc Max-Planck Institute, Tübingen, GERMANY, Williams, Pepper Textbook Developer, Portland, OR,
Current: Patrick Foo, Jessie Peissig, Yi Cheng, Chun-Chia Kung, Wendy Zosh
Totals: Graduate students: 11 Postdoctoral scholars: 4

William H. Warren

a. Professional Preparation

Hampshire College, Amherst, Mass, Psychology, Biology & Philosophy, B.A. 1976
University of Connecticut, Storrs, Conn, Experimental Psychology, M.A. 1979
University of Connecticut, Storrs, Conn, Experimental Psychology, Ph.D. 1982
University of Edinburgh, Scotland, Visual-motor control, Post-doc, 1983

b. Appointments

1982-	Assistant (1982), Associate (1988), and Full (1992) Professor, Brown University
2001-02	Invited Professor, University of Paris XI and University of the Mediterranean, Marseille, France (Benoit Bardy and Reinoud Bootsma, sponsors)
1995-96	Visiting Professor, University of California, Berkeley (Martin Banks, sponsor)
1989	Fulbright Research Scholar, Utrecht University, The Netherlands (Jan Koenderink, sponsor)
1983	NIH National Research Service Award, University of Edinburgh, Scotland (David Lee, sponsor)

c. Publications

(i) Five most closely related publications.

Laidlaw, D.H, Kirby, R.M., Davidson, J.S., Miller, T.S., da Silva, M., Warren, W.H., & Tarr, M. (2002) Quantitative comparative evaluation of vector field visualization methods. *IEEE Conference on Visualization 2001*, Piscataway, NJ: IEEE.

Fajen, B.R. & Warren, W.H. (2003) Behavioral dynamics of steering, obstacle avoidance, and route selection. *Journal of Experimental Psychology: Human Perception and Performance.,* 29, 343-362.

Duchon, A.P. & Warren, W.H. (2002) A visual equalization strategy for locomotor control: Of honeybees, humans, and robots. *Psychological Science, 13,* 272-278.

Warren, W.H., Kay, B.A., Duchon, A.P., Zosh, W., & Sahuc, S. (2001) Optic flow is used to control human walking. *Nature Neuroscience, 4*, 213-216.

Li, L. & Warren, W.H. (2000) Perception of heading during rotation: Sufficiency of dense motion parallax and reference objects. *Vision Research, 40,* 3873-3894.

(ii) Five other publications.

Warren, W.H. (2004) Optic flow. In L. Chalupa & J. Werner (Eds.) *The Visual Neurosciences.* Cambridge, MA: MIT Press, 1247-1259.

Li, L. & Warren, W.H. (2002) Retinal flow is sufficient for steering during observer rotation. *Psychological Science, 13,* 485-491.

Fajen, B.R., Warren, W.H., Temizer, S., & Kaelbling, L.P. (2003) A dynamical model of visually-guided steering, obstacle avoidance, and route selection. *International Journal of Computer Vision*, in press.

Yilmaz, E. & Warren, W.H. (1995) Visual control of braking: A test of the tau-dot hypothesis. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 996-1014.

Warren, W.H. & Hannon, D. (1988) Direction of self-motion is perceived from optical flow. *Nature, 336,* 162-163.

d. Synergistic Activities

Teaching: Received Brown's Elizabeth Leduc Award for Teaching Excellence in the Life Sciences (1995-7). Obtained course development grants to create an interdisciplinary course on "Perception, Illusion, and the Visual Arts," and recently developed a Web-based version. Developed Mac-based software for the interactive teaching of a cognitive psychology laboratory course, allowing students to design and carry out their own experiments.

Research Tools: Co-founded the Virtual Environment Navigation Lab, currently the largest virtual reality lab in the world (in collaboration with Drs. Michael Tarr and Leslie Kaelbling, with NSF funding). The 40 x 40 ft lab is designed to study visual navigation, visually controlled action, and visual cognition.

Service: Served on the NSF Committee of Visitors in Behavioral and Cognitive Sciences (2003), on the NSF Advisory Panel on Human Cognition and Perception (1995-1998), on the Editorial Boards of the *Journal of Experimental Psychology: Human Perception and Performance; Journal of Motor Behavior; Human Movement Science;* and *Ecological Psychology,* and on the Board of Directors of the International Society for Ecological Psychology (1986-present).

e. Collaborators and Other Affiliations

(i) Collaborators: Dr. Leslie Kaelbling, MIT; Dr. Michael Tarr, Brown University; Dr. Benoit Bardy, University of Paris; Dr. Reinoud Bootsma, University of the Mediterranean; Dr. Dagmar Sternad, Penn State University; Dr. David Laidlaw, Brown University; Dr. Lucia Vaina, Boston University

(ii) Graduate and Post-doctoral advisors: Dr. Michael Turvey, University of Connecticut; Dr. Robert Shaw, University of Connecticut; Dr. David Lee, University of Edinburgh.

(iii) Thesis Advisor and Postgraduate-Scholar Sponsor: Dr. Nicholas Hatsopoulos, University of Chicago; Dr. Daniel Mestre, CNRS, Marseille; Dr. Benoit Bardy, University of Paris XI; Dr. Fred Diedrich, Aptima, Inc.; Dr. David Bennett, Rhode Island College; Dr. Andrew Duchon, Simpli.com; Dr. Jeff Saunders, University of Rochester; Dr. Li Li, NASA Ames Research Center; Dr. Steven Finney, Spirent Communications; Dr. Brett Fajen, Rensselaer Polytechnic Institute; Dr. Bruce Kay, University of Connecticut; Dr. Melissa Kearns, Ibis Consulting; Dr. Philip Fink, Florida Atlantic University; Dr. Patrick Foo, Brown University; Dr. Alexandra Chardenon, Brown University.
Total graduate students advised: 14
Total post-graduate scholars sponsored: 8

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **David Laidlaw**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Multivalued MRI acquisition, visualization and dissemination**

Source of Support: **NIH (subcontract from Caltech)**

Total Award Amount: $ **100,108** Total Award Period Covered: **09/01/01 - 08/31/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Normal and abnormal in vivo carpal bone motions**

Source of Support: **NIH (subcontract from Rhode Island Hospital)**

Total Award Amount: $ **291,600** Total Award Period Covered: **04/01/01 - 02/28/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **1.00** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **ITR/HCI+ACS: Visualization of multivalued scientific data: applying ideas from art and perceptual psychology**

Source of Support: **NSF**

Total Award Amount: $ **2,296,599** Total Award Period Covered: **09/01/00 - 08/31/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **1.50** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **CAREER: Shape capture and modeling for wrist dynamics and ancient pottery analysis using manifold surfaes and signed-distance volume images**

Source of Support: **NSF**

Total Award Amount: $ **323,873** Total Award Period Covered: **03/01/01 - 02/28/06**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **1.50** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **ITR/Collaborative Research: Perceptual optimization for data visualization**

Source of Support: **NSF (subcontract from UNH)**

Total Award Amount: $ **103,789** Total Award Period Covered: **09/15/03 - 08/31/06**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Summ: **0.00**

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*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **David Laidlaw**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **MRI+TDI-based tools for analyzing white matter variation**

Source of Support: **NIH**

Total Award Amount: $ **2,853,986** Total Award Period Covered: **09/01/04 - 08/31/09**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **1.50** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Effects of distal radius malunions on carpal kinematics**

Source of Support: **NIH (subcontract from RI Hospital)**

Total Award Amount: $ **241,078** Total Award Period Covered: **04/01/04 - 03/31/07**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.50** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Pathologic analysis of demyelination using MR microscopy**

Source of Support: **NIH (subcontract from CMU)**

Total Award Amount: $ **396,000** Total Award Period Covered: **04/01/04 - 03/31/09**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.75** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Virtual pathologic analysis of demyelination using MRI**

Source of Support: **NIH (subcontract from CMU**

Total Award Amount: $ **393,977** Total Award Period Covered: **01/01/04 - 12/31/09**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.75** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Modeling visual design knowledge for optimization of scientific visualizations**

Source of Support: **NSF**

Total Award Amount: $ **638,397** Total Award Period Covered: **07/01/04 - 06/30/07**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **1.00** Acad: **0.00** Summ: **0.00**

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **David Laidlaw**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Computational simulation, modeling, and visualization for understanding unsteady bioflows**

Source of Support: **NSF**

Total Award Amount: $ **0** Total Award Period Covered: **09/01/04 - 08/31/09**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **George Karniadakis**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Stochastic Spectral/hp Element Methods for CFD and MHD Simulations**

Source of Support: **AFOSR**

Total Award Amount: $ **77,000** Total Award Period Covered: **01/01/04 - 12/31/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **1.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Spectral Representations: Algorithms and Applications**

Source of Support: **DOE**

Total Award Amount: $ **663,015** Total Award Period Covered: **09/01/95 - 06/30/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **1.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **ITR: Visualization of Multivalued Scientific Data Applying Ideas from Art and Psychology**

Source of Support: **NSF**

Total Award Amount: $ **150,000** Total Award Period Covered: **09/01/03 - 08/31/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **ITR: Generalized Polynomial Chaos: Parallel Algorithms for Modeling and Propagating Uncertainty in Physical and Biological Systems**

Source of Support: **NSF**

Total Award Amount: $ **145,680** Total Award Period Covered: **09/01/02 - 08/31/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **1.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Uncertainty-Based Design Methods for Flow-Structure Interactions**

Source of Support: **ONR**

Total Award Amount: $ **99,797** Total Award Period Covered: **02/01/04 - 01/31/05**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **1.00** Summ: **0.00**

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **George Karniadakis**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Collaborataive Research:Stochastic Models for Convective Heat Transfer: Algorithms and Experimental Validation**

Source of Support: **NSF/Sandia**

Total Award Amount: $ **78,174** Total Award Period Covered: **09/15/03 - 08/31/04**

Location of Project: **Brwon University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.50**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Simulation of Magnetorheological Fluids: Microdevices and Self-assembled Structures**

Source of Support: **NSF**

Total Award Amount: $ **307,968** Total Award Period Covered: **01/01/04 - 12/31/06**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.50**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Multi-scale Physical Modeling for Microbubble Drag Reduction at High Reynolds Number**

Source of Support: **DARPA/PSU**

Total Award Amount: $ **295,850** Total Award Period Covered: **11/01/03 - 10/31/04**

Location of Project: **Brwon University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **1.00** Sumr: **0.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Computational Simulation, Modeling, and Visualization for Understanding Unsteady Biflows**

Source of Support: **NSF (THIS PROPOSAL)**

Total Award Amount: $ **0** Total Award Period Covered: **09/01/04 - 08/31/09**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **1.00**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **Peter Richardson**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **ITR/HCI+ACS: Visualization of multivalued scientific data: applying ideas from art and perceptual psychology**

Source of Support: **NSF**

Total Award Amount: $ **2,296,599** Total Award Period Covered: **09/01/00 - 08/31/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.50**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **Sharon Swartz**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Computational Simulation, Modeling, and Visualization for Understanding Unsteady Bioflows (CURRENT PROPOSAL)**

Source of Support: **NSF**

Total Award Amount: $ **0** Total Award Period Covered: **01/01/00 - 01/01/00**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **DISSERTATION RESEARCH: Gliding Aerodynamics and the Origin of Bat Flight**

Source of Support: **NSF**

Total Award Amount: $ **9,894** Total Award Period Covered: **06/01/04 - 05/31/05**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

PI: K. S. Breuer | Other Agencies (including NSF) to which this proposal has been/will be submitted: None

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Lorentz Force Conotrol of Turbulence"**
5-25020 Supplement to 5-25098
with Professor Karniadakis
Source of Support: **ONR**
Award Amount (or Annual Rate): **$216,708** Total Award Period Covered: **09/30/02 - 5/31/04**
Location Of Project: **Brown University, Division of Engineering, 182 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: **1.50** Acad: Sumr:

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Closed-Loop Control of Turbulent Flows"**
5-21080
Source of Support: **AFOSR**
Award Amount (or Annual Rate): **$300,000** Total Award Period Covered: **06/1/02 - 9/30/04**
Location Of Project: **Brown University, Division of Engineering, 182 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: Acad: **0.5** Sumr: **1.00**

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Engineered Bacterial Transportation Systems"**
with Professors Powers,
Berg and Huber
5-28020
Source of Support: **DARPA**
Award Amount (or Annual Rate): **$1,039,819** Total Award Period Covered: **06/30/02 - 02/29/04**
Location Of Project: **Brown University, Division of Engineering, 184 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: **2.00** Acad: Sumr:

Support: [ ] Current [X] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Real-Time PIV System for Closed-Loop Flow Control"**
"Equipment only"
Source of Support: **AFOSR/DURIP**
Award Amount (or Annual Rate): **$164,317** Total Award Period Covered: **5/1/04 - 4/30/05**
Location Of Project: **Brown University, Division of Engineering, 184 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Modeling Fluid-Solid Boundary Conditions in Complex Microfluidic Systems"**
5-22000
Source of Support: **Sandia National Lab**
Award Amount (or Annual Rate): **$288,630** Total Award Period Covered: **11/14/03 - 9/30/05**
Location Of Project: **Brown University, Division of Engineering, 184 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: **1.00** Acad: Sumr:

Support: [ ] Current [X] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"NIRT: Fluid Interactions with Ordered Nanoscale Structures"**
With J. Xu, J. Freund
and H. Johnson
Source of Support: **NSF**
Award Amount (or Annual Rate): **$1,682,959** Total Award Period Covered: **4/1/04 - 3/31/08**
Location Of Project: **Brown University, Division of Engineering, 184 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: **0.50** Acad: Sumr:

Current and Pending Support

PI: K. S. Breuer | Other Agencies (including NSF) to which this proposal has been/will be submitted: None

Support: [ ] Current [X] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"The Structure and Dynamics of Thin Film Liquid-Vapor Systems in Confined Microgeometries"**

Source of Support: **NASA**
Award Amount (or Annual Rate): **$452,554** Total Award Period Covered: **12/1/04 - 11/30/08**
Location Of Project: **Brown University, Division of Engineering, 184 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: **1.00** Acad: Sumr:

Support: [ ] Current [X] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Acquisition of a Confocal Microscope"**
W/Professors Crawford, ***Equipment only***
Palmore,Tripathi, Xu, Pelcovits and Tang ***This proposal***
Source of Support: **NSF/IMR**
Award Amount (or Annual Rate): **$117,597** Total Award Period Covered: **7/1/04 - 6/30/05**
Location Of Project: **Brown University, Division of Engineering, 184 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: [ ] Current [X] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Engineered Bacterial Transportation System"**
5-28020 Continuation
Graduate Student Support
Source of Support: **NAVY**
Award Amount (or Annual Rate): **$66,935** Total Award Period Covered: **1/1/04-6/30/04**
Location Of Project: **Brown University, Division of Engineering, 184 Hope Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: [ ] Current [X] Pending [ ] Submission Planned in Near Future [ ] Transfer Of Support
Project/Proposal Title: **"Computational Simulation, Modeling, and Visualization for Understanding Unsteady Bioflows"**
W/Profs. Laidlaw, Karniadakis, Swartz
"This proposal"
Source of Support: **NSF** **No effort for K. Breuer**
Award Amount (or Annual Rate): **$3,980,764** Total Award Period Covered: **9/04 - 8/09**
Location Of Project: **Brown University, Computer Science, 115 Waterman Street, Providence, RI 02912**
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **Fritz Drury**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: **None**

Source of Support:
Total Award Amount: $ **0** Total Award Period Covered: **01/01/00 - 01/01/00**
Location of Project:
Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **Michael Tarr**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Recognizing disguised faces(white paper)**

Source of Support: **DARPA**

Total Award Amount: $ **656,058** Total Award Period Covered: **09/01/03 - 08/31/07**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.50** Sumr: **1.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Learning minimal representation for visual navigation and recognition II**

Source of Support: **NSF**

Total Award Amount: $ **426,799** Total Award Period Covered: **09/01/03 - 08/31/07**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.50** Sumr: **0.50**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Perceptual expertise network (PEN)**

Source of Support: **James S. McDonnell Foundation(subcontract via Vanderbilt)**

Total Award Amount: $ **144,894** Total Award Period Covered: **01/01/00 - 01/01/00**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.50** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Categorization and expertise in human visual cognition II**

Source of Support: **NSF**

Total Award Amount: $ **363,684** Total Award Period Covered: **05/01/01 - 04/30/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **1.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **IGERT: Learning and action in the face of uncertainty:Cognitive, computational, and statistical approaches**

Source of Support: **NSF IGERT program**

Total Award Amount: $ **2,658,195** Total Award Period Covered: **09/15/98 - 08/31/04**

Location of Project: **Brown University**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Summ: **0.00**

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*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **William Warren**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Visual Control of Locomotion**

Source of Support: **DHHS**

Total Award Amount: $ **1,873,904** Total Award Period Covered: **12/01/03 - 11/30/08**

Location of Project: **Brown University/Cog&LingSci**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **2.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Learning Minimal Representation for Visual Navigation & Recognition II**

Source of Support: **NSF**

Total Award Amount: $ **426,799** Total Award Period Covered: **08/01/03 - 07/31/07**

Location of Project: **Brown University/Cog&LingSci**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.50**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

Laidlaw, Karniadakis, Breuer Laboratory Facilities - Brown University

Facilities are described in the following three sections. The first regards Computer Science and Engineering at Brown University and the second and third, Biological facilities at both Brown and Harvard Universities.

The Brown University Department of Computer Science provides leading-edge computing technology to all its faculty and students. Desktops are populated by over 425 systems running Linux, Solaris, and Windows XP. Most of these are custom systems configured and assembled by the department's technical staff. Components include an Athlon XP 1700 CPU, 512MB of memory, a GeForce3 graphics card, and a 20" color monitor. These systems are connected to the department's 100Mb switched Ethernet network with access to two T3 internet connections and Internet2 via the University's fiber-optic backbone. An 11Mb wireless network is accessible throughout the department.

We are currently in the process of setting up a laboratory for the study of Internet applications. This laboratory will include one or more large (eight or more processors) SMP machines, 120 or more dual-processor machines arranged in clusters, gigabit networking, 10 terabytes of storage, a Network Appliance FAS960 Filer with 2TB of storage, appropriate networking hardware, and commercial software for building and running large-scale web applications. The laboratory will also include a workspace with 20 workstations that can be used as a front end for experiments or as a class laboratory.

Seventy-three of these departmental systems, equipped with 18" flat panel displays mounted on articulated arms, populate one of the department's two electronic classrooms, a banked auditorium designed to integrate technology with teaching. This room also serves as the primary computer cluster for undergraduate computer science students. A second undergraduate classroom/laboratory is populated by 22 systems running Microsoft's Windows XP. The layout of this space makes it an ideal room for sections, seminars, and interactive learning. Four research labs further enrich the environment with specialized hardware and advanced workstations from a variety of vendors.

Supporting the desktops are an array of servers providing a wide range of services to the user community. Central file services are provided by an FAS940 Filer from Network Appliance. This device provides over 4.5TB of RAID 5 disk space available to all departmental systems. A cluster of 20 dual-processor (1.5GHz CPUs with 2GB of memory) Linux-based systems is available for computationally intensive research.. The facility is administered by the Department's eight-person professional staff.

The Department occupies the top three floors of the Thomas J. Watson, Sr. Center for Information Technology, a bright, open and inviting space. The undergraduate workstation labs share the first floor with other computer-equipped classrooms and clusters managed by the University's computer support personnel. The new Internet laboratory is being set up on the third floor.

Laboratories:

The Graphics Lab: The Graphics Lab in the department of Computer Science has Sun and SGI workstations as well as a number of PC and Macintosh computers.

Virtual Reality Laboratory: The Virtual Reality Lab contains two fishtank VR seats with Polhemus head tracking, an Ascension extended-range Bird tracker with three receivers, two Phantom haptic feedback devices made by Sensable Technologies and an ActiveDesk built by Input Technologies, Inc. (ITI) which was donated to our lab by Alias/Wavefront. We also use a StereoGraphics VR setup (LCD-shutter glasses and two Logitech 3D mice). A full audio/video non-linear editing system is used to record footage directly from workstation screens and to edit videotapes. We also maintain a World Wide Web site, which contains general information about our group and research projects: (http://www.cs.brown.edu/research/vis/).

Fluid Mechanics Laboratory: The Fluid Mechanics Laboratory at Brown University, directed by Professor Kenneth Breuer, is engaged in experimental, theoretical and numerical research in a wide variety of problems concerning biological fluid mechanics, animal flight, the mechanics of turbulent flows and the behavior of fluids at the micron scale. The lab maintains two low-speed wind tunnels, a water tunnel, micro-flow facilities and has several PIV, PTV and Hot Wire measurement systems. The lab consists of approximately 10 researchers (undergraduate, graduate and post doctoral) and received funding from Sandia, AFOSR and ONR.

Center for Fluid Dynamics: The Center for Fluid Mechanics at Brown University maintains a research computing facility primarily supporting Applied Mathematics. The Center houses an IBM SP2 supercomputer with 24 Thin-2 nodes, each with 128MB memory, an SGI-O2000 (4-nodes), and a SUN E5000 (6-nodes) all obtained through NSF and AFOSR grants to Karniadakis.

Major Equipment:

Cave - Brown's Center for Scientific Computing & Immersive Visualization consists of several parallel computer systems with more than 100 IBM SP processors and a 4-wall virtual immersive facility (Cave). The Cave is driven by either an IBM SP or an SGI 8-processor O2000. This facility was started in May 1999 with funding from an NSF-MRI and a generous donation by IBM both in equipment and in-kind. Researchers at Brown, including the PI and Co-PI (Laidlaw and Karniadakis), have developed unique software for multi-modal interaction within the Cave for flow visualizations and for ``on-the-fly'' simulation steering. The same facility also houses three fishtank VR seats and a large single-wall head-tracked stereo display.

Venlab - A 40'x40' immersive interactive environment utilizing a head-mounted display.

High Resolution Stereoscopic Display - A high-resolution stereoscopic display enables us to carry out studies in information psychophysics close to limits of the resolution of the human visual system. This comprises two 9 megapixel displays arranged in the form of a classic Wheatstone stereoscope with surface mirrors to bring the images on the two monitors into registration resulting in an 18 megapixel display equal to the resolution of the human visual system. The displays are driven by a cluster of computers with high-end graphics cards and uses our own software to display the moving patterns for our studies. Using this apparatus we can generate real-time smooth stereoscopic displays of detailed information structures.

Swartz Laboratory Facilities – Brown University

Laboratories: An approximately 3000 square foot laboratory complex is available for use by Swartz and students in the Biomedical Center. It includes a hard and soft tissue histology lab, an image analysis lab, and an animal locomotion lab equipped with small wind tunnel, treadmills, runways, and high speed digital videography facilities. The Laboratory for Fluid Mechanics at Brown University, Division of Engineering, is fully equipped for conducting diverse range of studies in fluid mechanics. The lab is fully supported by computing workstations, computational fluid dynamics software, hardware and software for data acquisition, control, and post-processing of large data sets. The lab supports approximately four graduate students, two post docs, a number of undergraduate research assistants and a full-time technician. Additional laboratory facilities are available for use at the Harvard University-Concord Field Station, including a large wind tunnel building. Lab space is available within the Department of Computer Science for graphics and visualization work (Graphics Lab).

Animal: The Animal Care Facility (ACF) is a resource of the Division of Biology and Medicine and is housed primarily in the Biomedical Center; animals will be housed at the HU-Concord Field Station Animal Facility. Both the ACF and the HU-CFS are fully accredited by the AAALAC, are licensed and inspected by the USDA, and maintain a standing IACUC.

Housing. Care is available for both laboratory and wild species.

Computer: The Swartz laboratory has an 2 G4 PowerMacs, 4 G4 Powerbooks with data acquisition and analysis capabilities , and two Pentium-processor-based PCs. Shared EEB laboratory facilities include other Mac and PC computers and associated hardware and software for data acquisition and analysis and image processing.

Office: Swartz has an office one floor away from the laboratory facilities. Lab facilities include desk spaces for up to three additional people, including postdocs and graduate students. Office space for the department Administrative Assistant is in an adjacent room.

Major Equipment: The Swartz lab possesses 2 Redlake PSI high speed digital video cameras, capable of imaging rates up to 1000 Hz, and associated hardware for digital data acquisition and reduction of multi-camera views to 3-D data.

Other Resources: Biology and Medicine Machine Shop - wide range of tooling equipment, & professional machinist available on a fee-for-service basis. The Department of Ecology and Evolutionary Biology is served by 2 full-time administrative assistants (for 12 faculty plus the Anatomical Gift Program) who are available for routine secretarial services, ordering supplies and equipment, etc. Other significant experimental facilities for this project are located at the Harvard University Concord Field Station. The HU-CFS maintains a large animal care facility that houses both laboratory and wild animals. There is also a dedicated wind-tunnel building used exclusively for animal flight studies.

Lauder Laboratory Facilities – Harvard University

Laboratory: Laboratory and office space is provided in the Museum of Comparative Zoology, Harvard University. A separate aquarium room attached to the Lauder laboratory is temperature- and light-controlled, has air lines for aquaria, water filtration, and is approved by the campus IACUC as a satellite facility for holding fishes. A larger temperature-controlled aquarium room is located on the floor below the main laboratory. Separate rooms are used for video digitizing, specimen dissection, and computer data analysis. Another room houses graduate students and postdoctoral fellows, and a small conference room is used for lab meetings. Equipment is located in the main lab room, and is moved into the aquarium room as necessary for experiments. The main laboratory room also houses two flow tanks, one typically devoted to salt water research and the other filled with fresh water.

Animal: Animals are housed either in the laboratory or in the two aquarium rooms. We house both salt and fresh water fishes long term, and we perform all day-to-day care and maintenance ourselves.

Computer: The Lauder laboratory has both Macintosh and IBM compatible personal computers for data acquisition and analysis. Two computer systems are dedicated to the analysis of particle image velocimetry data.

Major equipment: Video data acquisition occurs via either a one-camera NAC Hi-DcamII high-speed digital video or a two-camera Redlake MotionScope PCI500 digital video system. Both video systems are housed in the laboratory. Lauder has a DcamII system, and two two-camera Redlake systems, so that a total of 4 Redlake cameras can be used simultaneously. Lauder has a TEAC XR5000 14-channel FM tape recorder, 12 Grass P511J preamplifiers and two power supplies for recording muscle activity data, and a 16 channel Powerlab analog-digital converter attached to a computer for acquisition of analog signals. These signals and digital video can be synchronized during data acquisition. Two Panasonic VCRs allow field-by-field review of video tapes as needed. A Grass stimulator for verification of electrode implantations is present in the lab. A

Coherent Innova I310 10 Watt continuous-wave argon-ion laser and power supply are used for DPIV data acquisition in conjunction with high-speed video.

Other resources: Harvard University has a fully equipped and well-staffed machine shop; service is performed for recharge to grants. The Lauder lab also has a small shop with drill press, table saw, band saw, grinder, and miscellaneous tools for construction of experimental equipment.

The Ichthyology Department in the Museum of Comparative Zoology houses approximately 1.26 million specimens that greatly facilitate comparative anatomical investigation. Lauder is Curator of this collection which is available to support the research proposed here at no cost to NSF.

From: itr@nsf.gov
To: dhl@cs.brown.edu
cc: ccfitr@nsf.gov
Subject: ITR Letter of Intent Submission Notice
Date-Sent: Wednesday, January 14, 2004 3:16 PM -0500

This is a notification of an ITR letter of intent submission. The information below was collected:

Letter of Intent ID: 2766

Title: Computational Simulation, Modeling, and Visualization for Understanding Unsteady Bioflows
Primary Division: CCF
Secondary Division: CNS
Tertiary Division: EF

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Project Description:
We propose to develop and evaluate computational modeling, simulation, visualization, and data-analysis tools and apply them to specific scientific areas involving time-varying flows near complex 3D boundary shapes.

Computational modeling research beyond direct numerical simulation will include modal analysis (proper orthogonal decomposition) to create parameterized flow solutions in which the parameters allow `what if' questions to be posed interactively. With these and other parameterized solutions, we will be able to interpolate across relatively large gaps in experimental data, allowing more effective comparison with simulated results and permitting more thorough and effective 3D visual analysis.

Interactive visualization tools will be developed for immersive virtual-reality display devices, including an existing Cave and a desktop system with resolution at the human acuity limit. We will develop these methods in our research group and in a novel interdisciplinary class of both visual design students and computer science students; the students will use new visualization prototyping tools that help leverage visual-design knowledge in this unfamiliar interactive 3D medium. A novel evaluation framework for 3D flow visualization methods will be created and applied to compare the efficacy of existing and proposed visualization methods. This framework will combine approaches from perceptual psychology, art history, and art education to characterize the strengths and weaknesses of visualization methods. As the evaluation system is used, it will capture knowledge about effective visualization and we will mine that knowledge to create a system for improving visualization m ethods automatically.

While our focus is on the development of computational tools, they will be designed with three driving scientific applications as a guide and test of their efficacy. First, blood flow in moving, deforming cardiac artery models will be studied to better understand atherosclerotic lesion formation and platelet-dominated thrombosis. Second, bat flight will be studied to better understand its mechanisms and evolution. Third, the movement of fish fins and their interactions with fluid will be studied to better understand fish propulsion. We will use experimentally acquired kinematic and flow data as well as simulated flow around models built from the captured motion. The two data sources will be complementary, each helping to validate results derived from the other.

Primary Priority Area: ASE
Secondary Priority Area:

Primary Technical Focus Area: SIM
Secondary Technical Focus Area: DMC

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ILLUSTRATION DEPARTMENT

RHODE ISLAND SCHOOL OF DESIGN

TWO COLLEGE STREET PROVIDENCE, RHODE ISLAND 02903-2784

Professor David Laidlaw
Department of Computer Science
Brown University
Providence RI

February 10, 2004

Dear David;

I am excited about collaborating on your NSF research proposal and the diverse aspects of the project work.

I know we agree that our recent Brown/ Rhode Island School of Design interdisciplinary class showed the potential of bringing artists and scientists together to solve tough visualization problems, but I think we have just scratched the surface of possibility for this kind of collaboration. I believe that our student artist/designers and faculty at RISD have unique expertise: a high level of visual acuity that will prove very valuable in the design process for scientific visualization. It is not often appreciated that visual psychology and the human response to visual stimulus are at the core of art and design, but this is in fact the case. If we are seeking to construct useful visualization tools for scientists, we must consider the visual interaction our hypothetical user will have with the model and design for maximum intuitive legibility. Artists are well positioned to anticipate and design for these reactions.

I've been reviewing the syllabus for our class in anticipation of the upcoming semester. I think we can expect to build effectively on the material we set out in the first class with even better results from the students, new insights into science/art collaboration and further refinement of the design qualities in our visualization projects.

I'm also looking forward to expanding my participation in your ongoing visualization research. In addition to my established role providing critical feedback on your visualization methods and participating in user studies to capture design knowledge for these 3D applications, I am planning to help identify additional designers who will work effectively on these problems with us. I understand that my non-teaching work will be compensated at $50/hour.

Thank you for your continued confidence in my contributions to your work and the opportunity to be a part of this tremendously exciting research.

Sincerely,

Fritz Drury
Professor of Illustration

MUSEUM OF COMPARATIVE ZOOLOGY
The Agassiz Museum

Lauder Laboratory

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February 5, 2004

Dear David:

I am most pleased to collaborate on your NSF grant "Understanding Unsteady Bioflows Through Simulation, Modeling, Visualization, Art, and Psychology."

My research on the biomechanics of fish locomotion is directly related to the aims of the grant, and I feel that you and the other P.I.s on the grant would be wonderful collaborators on the common problems that all of us face in attempting to understand complex biological flows.

Sincerely,

George V. L

George V. Lauder
Alexander Agassiz Professor of Zoology
Professor of Organismic and
Evolutionary Biology

List of All Personnel Associated with the Proposal:

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Vlada Aginsky, Microsoft
Eric T. Ahrens, Caltech
James Anderson, Brown University
Stuart Andrews, Brown University
Errol Arkilic, Redwood Microsystems
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