NATIONAL SCIENCE FOUNDATION
4201 WILSON BOULEVARD
ARLINGTON, VIRGINIA 22230

Dr. J. D. Andrade
Department of Bioengineering Educational
Studies
University of Utah
Salt Lake City, UT 84112

SEP 30 1999

RE: Proposal EEC-9876378

Dear Dr. Andrade:

We regret to inform you that the National Science Foundation is unable to support your proposal to establish a new Engineering Research Center for Bioengineering Educational Technology. We received seven proposals, and based on the recommendation of an initial panel, site-visited two of the proposed centers. As a result of the recommendations of the site visitors and a second panel, we have selected one of these proposed centers for funding.

The seven proposals received in response to this funding initiative were reviewed under the review criteria given in the Program Announcement "An Engineering Research Center for Bioengineering Educational Technology" (NSF 98-68). Each proposal was reviewed prior to the first panel meeting by a subset of these panelists, who then assigned it a rating. When they assembled at NSF, these panelists discussed each proposal and its individual reviews. On the basis of these discussions, the panel arrived at a consensus recommendation for each proposal to either site visit or not site visit the proposed center. After the two site visits recommended by this panel were completed, a second panel was convened to make the final recommendation.

For your information we have enclosed verbatim reviews on your proposal that contributed to this decision. If you have any questions regarding the process or the reviews, please contact Dr. Joy Pauschke, Program Director for the Engineering Research Centers Program, at (703) 306-1380.

Sincerely,

Marshall Lih
Division Director
Engineering Education and Centers Division

Enclosures

Copy to: Lynne Chronister
Authorized Org. Rep.

National Science Foundation
Engineering Research Centers Program
Program Announcement NSF 98-68
"An Engineering Research Center for Bioengineering Educational Technology"
September 16-17, 1998
ERC Panel Summary Cover Sheet

Proposal Number: 9876378
Lead Institution: University of Utah
Principal Investigator: J. D. Andrade
Title: From Simplicity to Complexity to Simplicity

Recommended for Site Visit _____ Not Recommended for Site Visit __X__

Strengths and Weaknesses:

Vision, Strategic Plan, and Deliverables

The proposal intends to expand and improve the undergraduate program in bioengineering at the University of Utah. The concept of a bio-based project throughout a four-year curriculum that is centered around an Internet simulation and information environment is truly novel when overlayed with a Simplicity - Complexity - Simplicity (SCS) theme, especially for biological and biomedical systems.

The strengths of the proposal are the ideas it advances for promoting educational development and reform in bioengineering, but the proposal does not, in general, really address improvement in educational technology. For example, the educational technology to be employed is primarily the Web. Ideas for implementing innovative educational technologies or doing research in educational technologies are limited, as the focus seems mostly limited to the program at the University of Utah. As such, it is not evident that the activities and deliverables of the proposed ERC will establish national leadership in developing next-generation educational technology in bioengineering.

Research Program

The research program proposed consists of three major thrusts, clustered around integrative bio-based projects. These research thrusts are adequately described, but it is not clear that an adequate plan has been developed to support these thrusts, or that a sufficient investment in technical infrastructure is being proposed. In addition, it is not clear how the proposed activities mesh with existing scientific research at Utah, or that these activities build upon current intellectual resources at Utah. For example, the proposal focuses upon a relatively new software company to provide scientific visualization tools, while the very well known scientific visualization group at Utah is not emphasized.

Pa.../...

One aspect of the research program that was generally regarded as a weakness by the panel was the proposed "Living Internet" activity. Although this is intuitively interesting, analysis of problems more directly related to bioengineering might be more useful in preparing students for their careers in bioengineering. Thus, the concept is interesting from an educational point of view, but it also has the potential of being somewhat misleading.

Education Program

The educational program is tied closely to the research program described above, and shares many of the same strengths and weaknesses.

The educational program is substantially focused at the undergraduate level. Although the project-based approach has intuitive appeal, care should be taken no ensure that the projects are structured so that students aren't "trapped" by the project structure. The panel felt that a program based on a student being involved in the same 4-year project was too risky. A project based approach from Freshman year up was generally liked, but would have been stronger if each year's project were more independent of each other.

Benefits at the graduate level expected to be the result of "trickling up." Rather than assuming that such benefits would naturally ensure from program activities, a more intentional effort to involve the graduate program would be a stronger approach.

Outreach and Dissemination Program Mechanisms and Activities

The outreach and dissemination program proposed is adequate and appropriate. The toolkits and Internet approaches are useful ways to disseminate products to the general community. The linkages through the summer program to K-12 education is an exciting idea. On balance, however, it is not clear how these activities will be of sufficient scale to achieve the national mission of the ERC.

Assessment and Evaluation Plan

The assessment and evaluation plan is somewhat limited in that it seems to focus upon computerized testing. Moreover, it is not clear how the use of an off-site assessment consultant will be the most effective way to generate information necessary to improve the proposed educational program.

Industrial/Practitioner Collaboration

The level of participation from industry seems rather weak, in that there is little firm commitment from industrial collaborators.

Leadership, Management, and Research Team and Infrastructure

The leadership and management team seems well qualified to implement the proposed activities.

Rationale for the Panel Recommendation

The activities in the proposal are very interesting from an bioengineering educational reform standpoint, in that the activities represent a sharp departure from current practice in bioengineering education. These activities do involve some interesting applications of educational technology, but the primary focus of the proposed activities is not in developing the next-generation of educational technology in bioengineering based on advances in our understanding of cognitive science. Moreover, the number of individuals directly affected by these proposed activities is relatively small, making it difficult to envision how the proposed ERC will provide national leadership in bioengineering educational technology.

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 98-2

NSF 98-68 07/28/98

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

ENGINEERING RESEARCH CENTERS

FOR NSF USE ONLY

NSF PROPOSAL NUMBER

9876378

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
				009095365	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN): 876000525

SHOW PREVIOUS AWARD NO. IF THIS IS
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IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYMS(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE: University of Utah

ADDRESS OF AWARDEE ORGANIZATION, INCLUDING ZIP CODE:
University of Utah
1471 Federal Way
Salt Lake City, UT. 841021807

AWARDEE ORGANIZATION CODE (IF KNOWN): 0036756000

NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE

ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING ZIP CODE

PERFORMING ORGANIZATION CODE (IF KNOWN)

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TITLE OF PROPOSED PROJECT: Bioengineering Educ: Simplicity to Complexity to Simplicity

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE
$ 9,954,225	60 months	04/01/99

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
☐ BEGINNING INVESTIGATOR (GPG 1.A.3)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.D.1)
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☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.12)
☐ GROUP PROPOSAL (GPG II.D.12)
☐ VERTEBRATE ANIMALS (GPG II.D.12) IACUC App. Date 01/01/00
☐ HUMAN SUBJECTS (GPG II.D.12)
Exemption Subsection_______ or IRB App. Date 01/01/00
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☐ RESEARCH OPPORTUNITY AWARD (GPG V.H)

PI/PD DEPARTMENT: Bioegineering Educational Studies

PI/PD POSTAL ADDRESS:
Salt Lake City, UT 84112
United States

PI/PD FAX NUMBER

NAMES (TYPED)	Social Security No.*	High Degree, Yr	Telephone Number	Electronic Mail Address
PI/PD NAME J. D Andrade	SSNs are confidential and are not displayed	Ph.D,, 1969	801-581-4379	
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

NOTE: THE FULLY SIGNED CERTIFICATION PAGE MUST BE SUBMITTED IMMEDIATELY FOLLOWING THIS COVER SHEET.

*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 NSF INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

List of Participants

Academic Participants:

Andrade, J.D.	Professor & Co-Chair, Dept. of Bioengineering, Univ. Utah
Bermudez, J.	Associate Professor, School of Architecture, Univ. Utah
Blair, D.	Associate Professor, Dept. of Biology, Univ. Utah
*Budinger, T.	Professor, Dept. of Radiology, Univ. California—Berkeley
Caldwell, K.	Chair Professor, Dept. of Biotechnology, Uppsala Univ (Sweden)
*Chauvet, G.	Professor & Director, Inst. of Theoretical Biology, Univ. of Angers (France)
Christensen, D.	Professor, Depts. of Bioengineering & Electrical Eng., Univ. Utah
*D'Argenio, D.	Professor & Chairman, Dept. of Biomedical Engineering, Univ. of Southern California
Frazier, B.	Assistant Professor, Dept. of Bioengineering, Univ. of Utah
Herbst, M.	Dept. of Bioengineering, Fachhuchschle Hamburg
Hlady, V.	Associate Professor, Dept. of Bioengineering, Univ. of Utah
Horch, K.	Professor & Co-Chair, Dept. of Bioengineering, Univ. Utah
Jaffe, C.	Professor, Dept. of Medicine, Yale University
Johnson, C.	Associate Professor, Dept. of Computer Science, Univ. Utah
Johnson, R.	Emeritus Professor, Dept. of Computer Science, Univ. Utah
Johnson, S.	Research Professor, Dept. of Bioengineering, Univ. Utah
Kern, S.	Assistant Professor, Depts. of Anesthesiology & Bioengineering, Univ. Utah
*Linehan, J.	Professor & Chair, Dept. of Biomedical Engineering, Marquette, Univ.
MacLeod, R.	Assistant Research Professor, Dept. of Bioengineering, Univ. Utah
*Onaral, B.	Professor & Director, School of Biomedical Engineering, Drexel Univ.
Othmer, H.	Professor, Department of Mathematics, Univ. Utah
Pantalos, G.	Research Professor, Dept. of Bioengineering, Univ. Utah
Price, R.	Professor, Dept. of Physics, Univ. Utah
Rabbitt, R.	Associate Professor, Dept. of Bioengineering, Univ. Utah
Romer, R.	Professor & Chair, Dept. of Mechanical Engineering, Univ. Utah
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*Walker, W.	Professor, Dept. of Biological Engineering, Utah State Univ.
Westenskow, D.	Professor, Depts. of Anesthesiology & Bioengineering, Univ. Utah
Wiley, S.	Associate Professor, Dept. of Pathology, Univ. Utah
Wiskin, J.	Associate Research Professor, Dept. of Bioengineering, Univ. Utah

Industrial, Practitioner, and Other Partners:

Ash, O.	Executive Director, ARUP, Inc. (Associated Regional University Pathologists, Inc.) a major clinical and diagnostic testing laboratory.
*Blake, L.	Vice President, Sorenson-Vision, Inc., Logan, Utah—a data compression company whose technology allows full time video over normal telephone lines.
DiCaprio, V.	Senior Vice President & Chief Technical Officer, Becton-Dickinson Co.
* Jacobson, S.	President, Sarcos, Inc., Salt Lake City, a pioneering and leading firm in robotics and advanced biomedical products (www.sarcos.com)
*Johnson, R.	Principle of nDV Ltd., whose unique parallel coordinates software is described in Thrust 3—Visualization.
McRea, J.	Chairman, Dept. of Bioengineering Industrial Advisory Board and President/CEO, Device-Based Therapeutics, Inc., Salt Lake City
Suggett, A.	Director of R & D, Smith and Nephew Ltd., London
*Van Wagenen, R.	Vice President for R & D, Protein Solutions, Inc., Salt Lake City

* letter in Appendix A

Project Summary

The University of Utah proposes an Engineering Research Center in Bioengineering Educational Technology (NSF-98-68) with the title "From Simplicity to Complexity to "Simplicity"" (SCS), with J.D. Andrade as principle investigator and Director.

We propose to develop and implement undergraduate and graduate curricula which will empower students, faculty, and practitioners to study, interpret, research, and apply the emerging field of bioengineering from a non-traditional set of perspectives, using a set of new as well as traditional tools. Our approach is based on the growing appreciation and realization that the spatial and temporal organization and interaction of living matter provides it with unique sets of properties and behaviors which cannot be understood using traditional reductionist and even synthesis approaches and tools. Although we must continue to use and apply those traditional tools, which have proven so powerful and effective, we can now add and develop powerful new tools and perspectives. Three research thrusts will develop such key tools.

We specifically propose to research, develop, and implement an integrated biology and engineering-based four year undergraduate curriculum using a set of complex and challenging bio-based projects as the basic structure. Students, faculty, graduate students, and advisors will compose teams with strong interests in a particular project. Graduate students will participate as mentors, advisors, teachers, and "senior" participants in the projects and courses. Industrial and academic bioengineering, biology, biotechnology, engineering, and medical professionals will participate in all aspects of the curriculum, including design and supervision of the projects. Participating institutions and corporations will play major roles.

The projects will be fully integrated over the four years of the curriculum. The projects themselves are considered a "research thrust." The program is designed primarily for those students who learn best by doing—by being involved in, committed to, and empowered by a challenging project. The different project teams will interact, educate, and empower each other. Many of the project topics and problems will be related to two or more projects. We expect considerable project synergism and cross fertilization.

A set of courses and related experiences will help provide knowledge, understanding, and tools directly applicable to the projects. The courses, seminars, and other experiences will connect and relate to the integrating project. Although project needs and interests will require traditional tools and courses, new tools and capabilities will be needed, including a set of bio-derived perspectives. The other three research thrusts will develop tools and resources needed for such complex and inclusive projects. These thrusts are the "Living" Internet, Multi-dimensional Visualization, and Modeling and Simulation.

We propose to utilize the Internet as a participation and involvement vehicle, as a research tool, and as a means for wide and effective dissemination of the curriculum, project progress, and related information. We further propose to use the Internet itself as a model for biological processes. Individual computer nodes and their human operators will represent and function as "self-motivated biological components." Students themselves will play the role of a particular biological reaction, function, or device and will interact with other students and functions through the net. We call this the "Living Internet." Analysis of the outputs of such complex experiments will likely lead to a greater understanding of their complexity.

The four year integrated project will be designed to implement our Simplicity—Complexity—"Simplicity" objective and theme. The bioengineering/pathological problem or need will be presented and dissected (reductionist) to enable "simple" subsystems and components to be modeled, studied, designed, constructed, and analyzed, always keeping the big picture—the complex problem—in mind. These simple components will then be assembled (synthesis) into more complex subsystems/systems, and the system's properties/characteristics will be measured and analyzed. Like living systems, the more complex systems will begin to exhibit complex behavior—new properties/behavior will emerge with the increasing complexity. As this complexity is characterized and analyzed, new and simple (but different!) rules will evolve and emerge—hence "simplicity" <u>from</u> complexity. We will apply many of the new, powerful, and rapidly evolving tools and concepts represented by the names complexity scaling, networks, hierarchy, parallelism, non-linear, chaos, and emergence.

We propose to evaluate and compare this approach with a more traditional approach, using our new undergraduate curriculum. Our first undergraduate class will begin in the Fall of 1999, utilizing a traditional undergraduate bioengineering curriculum. We will start this project-based experimental curriculum with a 15 to 20 person "freshman" class in Fall 2000. The project-based group will be assessed and compared with the parallel, traditional class for the entire duration of the grant.

We also propose an extensive high school and general public outreach effort, building on our existing outreach activities, emphasizing the involvement and participation of minority populations. Summer workshops will help provide high school students and some of their teachers with the motivation and skills to address bioengineering topics and problems.

We will establish a set of advisory boards. An International Advisory Board (IAB) will focus on project-based undergraduate education and will include individuals with experience in the key research thrusts. The group will meet annually at the University of Utah to provide advice, critique, and assessment. We will also have a rich seminar and visiting faculty program, focused on the research thrusts and project topics. These advisors and visitors will actively participate in the program and in specific project groups. Strong international participation will be a key emphasis. The Academic and Industrial Advisory Council, composed of representatives of the participating institutions and companies, will meet twice a year, one of those meetings joint with the IAB.

The project will be managed by an Executive Committee, responsible for the day to day management and conduct of the project.

The project's experiences, output, and deliverables will be disseminated to the community via an aggressive program of faculty lectures and visits to other institutions, particularly in years 3-8. We will also participate extensively in the meetings of the Biomedical Engineering Society, the American Society for Engineering Education, the Engineering in Medicine and Biology Society, and the American Institute for Medical and Biological Engineering. We will also develop internet and video/multi-media vehicles for effective dissemination and delivery, as well as for assessment purposes.

We propose a five year effort with an anticipated three year renewal (eight years total). The University and the Department are committed to maintaining the program as NSF funding is phased out in years 6-8.

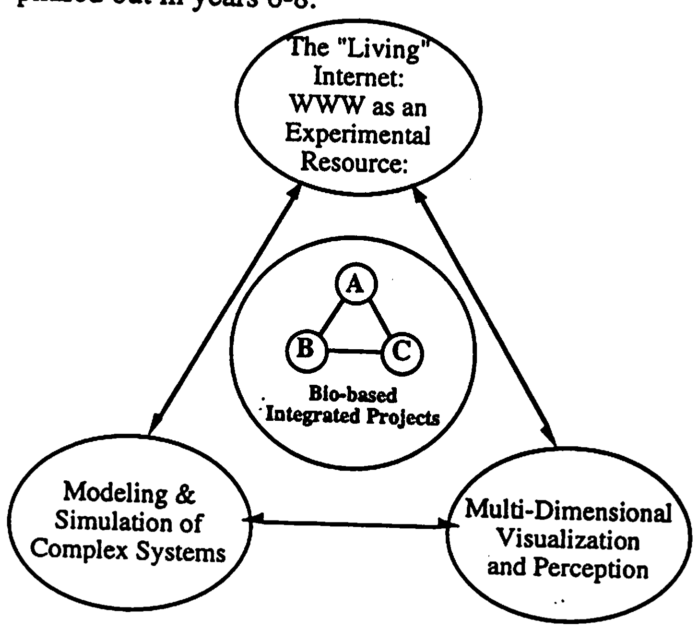

Figure 1. Key components & projects of the ERC in Bioengineering Education Technology: Simplicity <--> Complexity --> "Simplicity. The small group bio-based integrated projects, discussed in Sections D and F, are the key integrating and motivational parts of the program. Dealing with such challenging projects at the undergraduate level requires a set of skills and tools to facilitate learning, analysis, and design. Three key research thrusts of the project will such tools, represented in the three outer ellipses and described in Sections D and F.

University of Utah

NSF ERC BET:
From Simplicity to Complexity—to "Simplicity"

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References

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D. Facilities and Equipment (Form 1363)
E. Current and Pending Support (Form 1239)
F. Justification for Secretarial and Administrative Support

A. Vision, Goals, and Rationale

Vision

We have a dream. We dream of an integrated, motivated, creative, and practical undergraduate experience which will help students, graduates, faculty, and practitioners evolve the skills and interests to address problems and opportunities in a renaissance-like, "conciliate" (1), holistic manner. We dream of students and colleagues who choose to work on less defined and complex problems and are stimulated by, indeed addicted to, the intellectual and inventive challenges which such problems demand. Part of our dream involves participants who do not accept the often common attitude in the engineering and education community that "renaissance," unitary, conciliate, or holistic approaches equate to superficiality. We believe that the human mind has the capabilities and even the need to develop an integrated, coherent view of complex phenomena with as much detail and depth as may be required. We firmly believe that students at all levels are generally inefficiently and inadequately stimulated and motivated, but that their potential for enhanced learning and development is almost infinite.

We will work with groups of appropriately selected students to help them evolve strong backgrounds in the basic sciences, mathematics, and engineering at the undergraduate level. They will concurrently develop strong backgrounds in complex, integrated, interdisciplinary projects which will challenge, enhance, and expand their mathematics, scientific, and engineering skills. With their engineering design and project development skills, these engineers will be well equipped to tackle complex bioengineering projects.

We will use a Simplicity to Complexity to "Simplicity" (SCS) approach. By this we mean that students will be exposed to topics and projects in a societal context, then rapidly and efficiently apply reductionist principles to break the project down to simple, fundamental primitive components and models which can be individually studied using their appropriate scientific, mathematical, and engineering backgrounds. As background knowledge and expertise are acquired, the simpler building blocks will be connected: the synthesis approach. As those more complex, multi-component systems are studied and characterized, new tools will be used to facilitate their analysis and understanding. As the project evolves in complexity, students will discover and appreciate that complex systems may exhibit non-linear characteristics (2). As the project proceeds, their enhanced analytical and engineering skills will allow them to evolve guidelines and even sets of rules for their now complex system (2, 3). This new "simplicity" will not be an extrapolation or additivity of the original simplicity, which was achieved by reduction to individual components or building blocks, but rather will be a "simplicity" achieved by analyzing the now complex system from a different hierarchical perspective (2). Such experiences will give them the perspective and experience to tackle complex systems and problems in their future endeavors.

We really do want to produce Leonardo da Vinci-like individuals, whose creativity, ideas, and inspiration are matured and modulated by engineering ethics and the need to complete and deliver projects on time, under budget, and with enhanced specifications and performance.

Our dream is to produce such unique individuals and to develop faculty and practitioners who can disseminate these experiences and processes to the broader community.

Our goal is to apply this conciliate, renaissance-like approach to undergraduate and graduate bioengineering education. We believe that this will be one of several steps in the significant restructuring and enhancement of Engineering in general (4-6). The challenges and problems our society and civilization must now confront, in our opinion, require nothing less.

Goals

Our primary goal is to design, develop, and implement a complex project-based bioengineering curriculum. The immediate product or deliverable will be the students prepared via

In designing an undergraduate bioengineering program, it is important to recognize the interdisciplinary nature of the field. Biomedical engineers are faced with a wide variety of tasks covering all fields of engineering, physics, chemistry, mathematics, and the life sciences. The diverse nature of the field sometimes leads to curricula that survey a wide number of topics, forcing the students to memorize a large set of "factoids". The engineering approach, however, requires dexterous deductive reasoning to solve practical problems. It is therefore important to establish within each student a solid foundation upon which he or she can build. Graduates must be able to dissect the problem, recognize salient physical principles governing the situation, and apply the scientific methods to arrive at a solution. In this spirit, we have designed a rigorous undergraduate program that we believe will provide this training and prepare students for the future.

We are committed. The timing and resources are in place. We are eager to begin this experiment.

B. Bioengineering Education and Curricula

In its 1995 Survey of Academic Bioengineering Programs, the American Institute for Medical and Biological Engineering (AIMBE) noted that the most often cited skill acquired by graduates of bioengineering programs was "research/problem solving," followed by "work at the engineering/medicine interface" (9). However, the most cited need in undergraduate programs was for "active involvement with other disciplines, primarily in application areas in the life sciences". Although there was agreement that biomedical engineering is and will continue to be an engineering discipline, current undergraduate programs in the field are viewed as primarily serving to prepare students for graduate school, rather than for careers in biomedical engineering, per se, in spite of the fact that less than 25% of bioengineering graduates end up in academic careers. Clearly the field would benefit from an undergraduate curriculum that better prepares graduates for both academic and nonacademic careers.

A survey of curricula from some of the more prominent undergraduate programs in the country shows that they all tend to follow the traditional academic approach: students start with basic courses in math, physics and chemistry, and only later get into subjects that are directly affiliated with their major interests. The typical rationale for such an approach is that students need the basics before they can understand or appreciate the more specialized, "advanced" topics of a specific engineering discipline.

The shortcoming of this approach, as the Colorado Commission on Higher Education's Physics-2000 Project points out (10), is that there is little context in which the students can place this material with respect to their interests, which interferes with learning. Rather, by "proceeding from familiar technological devices to the abstract underlying concepts", the subject "is made more relevant and the (student) is motivated to explore abstract ideas." In biomedical engineering, this might take the form of simulating or interfacing with one or more anatomical/physiological systems of the body, from which one would quickly come to appreciate the need to have a basic understanding of physics and chemistry, and to have the mathematical tools to apply these principles to a living system.

It is often claimed that such an approach is unworkable because students can't hope to obtain any sort of understanding of something as complex as a physiological system without a background in calculus, differential equations, and matrix algebra. However, it should be kept in mind that these are just artifacts—tools—created by man in an attempt to make analysis of certain classes of natural events more amenable to solution. In principle, with the power of modern day desktop computers, by solving difference equations directly rather than by limiting oneself to those subset of problems for which closed form solutions using calculus are possible, the student can obtain a more intuitive insight into the process being modeled and is free to look at a broader range of more interesting, non linear problems. It is the latter, of course, that makes the study of living processes in general, and bioengineering in particular, such an interesting challenge. Similarly, once one starts studying living processes, it quickly becomes apparent that knowledge of organic chemistry, thermodynamics, properties of materials and mechanics is essential to understanding what is going on.

This approach also has the advantage of mimicking how science itself has developed. It is not the development of analytical tools that drives scientific exploration. Rather, it is the challenge of understanding complex, existing natural phenomena that leads to the development and application of mathematical and physical tools to scientific endeavors. By presenting students early on with a "real life," relevant, practical problem to be solved over the course of their undergraduate careers, we expect them to be better motivated not only to take the basic course work in math, physics and chemistry, but to actually learn the material well (as distinct from simply getting high grades in the courses) since they will have a better appreciation of how it can help them achieve a goal of real interest to them.

This approach and argument is applicable to engineering education in general (4). The National Academy of Engineering and the National Research Council's report "Engineering Education in Practice in the United States" (5) has argued for very significant changes in undergraduate engineering education, including a project-based emphasis. Although many schools do indeed include project-based education in their undergraduate curricula, there are very few which utilize the four year integrated project approach as we propose here.

C. Value Added by the ERC

Please refer to sections D (Strategic Plan) and E (Delivarables).

D. Strategic Plan

Overview

The key components and projects are presented in Figure 1, already given in the Project Summary.

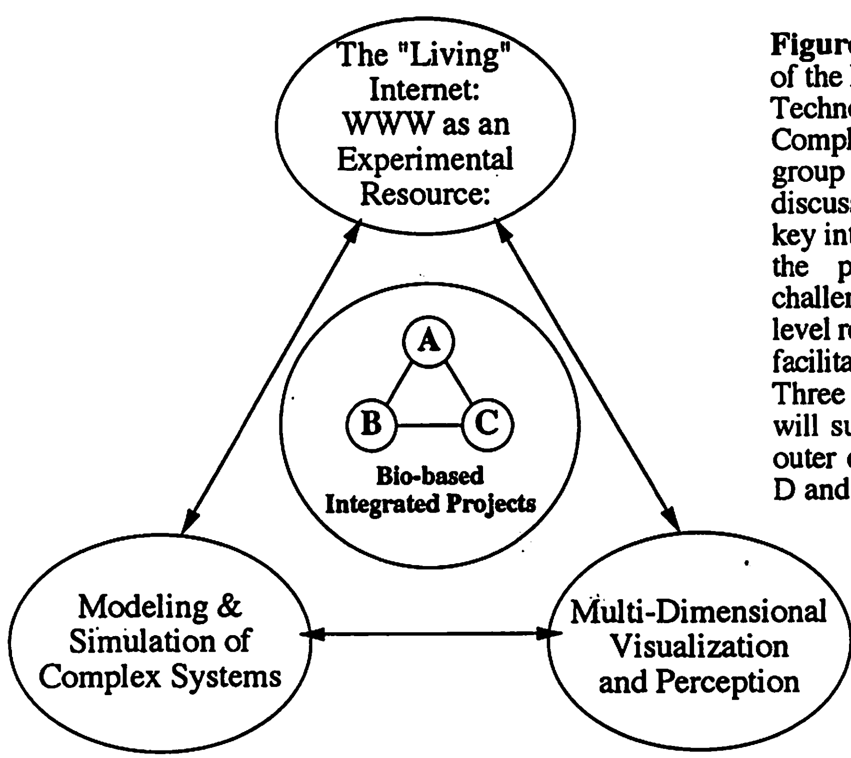


Figure 1. Key components & projects of the ERC in Bioengineering Education Technology: Simplicity <--> Complexity --> "Simplicity. The small group bio-based integrated projects, discussed in Sections D and F, are the key integrating and motivational parts of the program. Dealing with such challenging projects at the undergraduate level requires a set of skills and tools to facilitate learning, analysis, and design. Three key research thrusts of the project will such tools, represented in the three outer ellipses and described in Sections D and F.

Thrust 1: Bio-Based Integrated Projects: The Core of the Curriculum (K. Horch and D. Christensen)

The students we attract will have strong interests in significant societal problems. They will also have strong interests in the physical sciences, the life sciences, and in engineering/technology.

The undergraduate bioengineering program utilizes a set of complex, open-ended, integrating projects and teams. Figure 2 presents the pedagogic rationale for the integrated four year bio-based, complex project as the key component of this new curriculum. Time is represented vertically. Much of the first semester will be devoted to the development of the big picture, a comprehensive integrated view or perspective of the various projects (the base of the cone in Figure 2). The students will then be assembled into their respective teams based in large part on their interests and aptitude. They will then simplify the project, applying the traditional reductionist approach. The shaded area at the base of the cone (Figure 2) represents their accumulating academic and engineering knowledge. As time proceeds that knowledge increases, but project needs will define and demand additional knowledge and tools. Those tools and knowledge will be acquired via traditional courses, as well as by special project short courses, laboratories, and self-study. The information and skills will be applied to the project, whose growing complexity will then demand additional knowledge and tools, and the cycle will continue. At the conclusion of the four years, the student will have a broad and yet deep knowledge in most relevant fields, together with an unusually rich and comprehensive tool and skill set. Perhaps most importantly, the students will have the interest and confidence to deal with complex problems and projects.

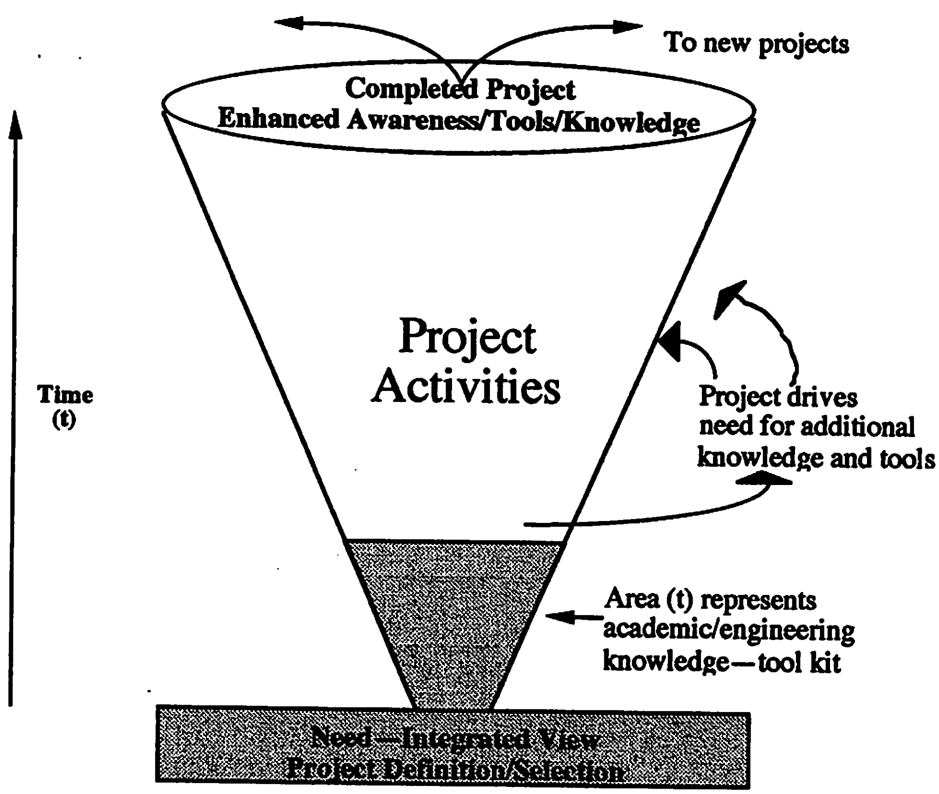


Figure 2. The integrating project as a driver/motivator for education (see text for complete description). Refer also to Figure 3.

Figure 3 shows the approximate credit distribution between traditional courses and project-based activities.

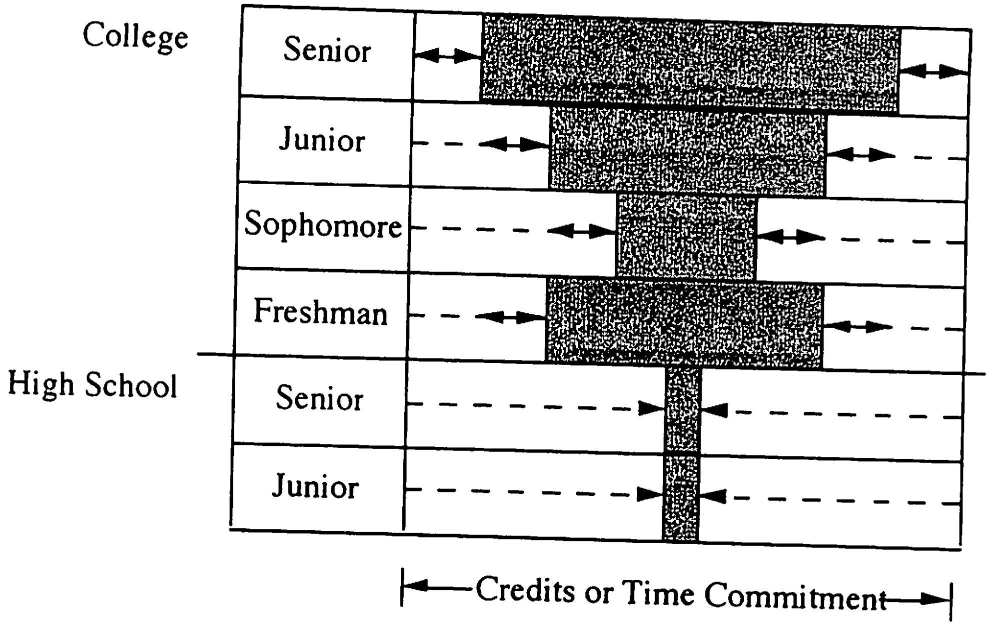


Figure 3. Schematic of the general structure of the curriculum. The central shaded zones represent project activities—research, design, assembly, testing, and analysis. Time and effort in courses and related traditional means of instruction and learning are indicated to the left and right of the central project zone. The arrows simply denote that the courses will connect and relate to the central projects, and vice versa. Many topics included in traditional bioengineering undergraduate curricula are integrated and contained within the project zone, as project activities also involve lecture/simulation/demonstration components. Over half of a student's credits and time over his/her four year programs are in project-based activities.

Complex projects require the learning and appreciation of traditional engineering and scientific knowledge. But they also require new or non-traditional tools, so the students, faculty, and staff can effectively deal with the complexity of these problems. The development of such tools is the objective of the other research thrusts.

The projects developed and conducted to meet this range of interests and motivations must be challenging and relevant but doable. We prefer that they be bio-based, that is have a biological basis to help facilitate the learning of biology. A key challenge is how to select projects which are complex, challenging, relevant and novel and which can provide the connections needed to meet our educational objectives. These projects must also be of interest to our faculty, to visiting faculty from participating institutions, and to our graduate students, as they are all key components of each project team. In subsequent years of the program, we expect projects to be suggested by the students themselves. We will actively solicit project suggestions through the community, possibly from contests or competitions.

We will formulate three such projects per year. From year five on, at steady state, twelve project groups will be working in parallel. Although, there will be considerable synergism and interaction among these projects, they are indeed distinct, consisting of a team of five undergraduate students and of the order of five faculty, graduate students, technical staff, and key advisors (Figure 4). This means about 100 individuals actively involved in the steady state phase of the program.

A preliminary matrix of projects is given in Table 1. Projects A, B, and C listed for Class 1 (2000-2004) could be considered somewhat traditional, albeit exceptionally challenging. One could think of the A Project List as representing sensory and neurophysiology interests and activities. The Project B list represents chemistry and biochemistry, together with tissue engineering and biohybrid devices. The Project C list tends to reflect a biomechanics emphasis. Our faculty has interests and activity in all twelve of these topics. We will briefly describe our approaches to Projects A, B, and C in Section F.

Each project team will develop multiple approaches to each of their long range goals. For example, the project on vision could involve a very strong bio-based and even tissue engineered component, as well as a more traditional photonic device, electro-optical instrumentation approach. The same could be said for the biomimetic liver: one can consider a substitute approach (transplantation), a purely chemical or biochemical engineering approach, and a tissue engineering or biohybrid approach. Although the faculty on the project teams will have their own ideas, each student team will evolve and develop its own relevant approaches to the challenge.

We will begin the project-based class in Fall of 2000 (see time line in section D). We are assuming NSF funding begins in April 1999. That gives us one year to recruit and hire appropriate staff, visiting faculty, and others, and to work closely with our team of advisors and participating institutions to fully formulate and organize the program. It also gives us a year to remodel and equip the needed project-based laboratory space.

Our mission is to provide an environment which will enable the students to address complex problems from both biological and engineering perspectives, and to enjoy and almost literally revel in the complexity itself.

Table 1. Bio-Based Integrated Projects for SCS ERC Program (tentative).

Class/Dates	**Projects (Tentative)**		
	A	B	C
Class 1 (2000-2004)	Neuromimetic Systems: Vision	Engineering Bioenergetics	Cardiomimetic System
Class 2 (2001-2005)	Biomimetic Hearing	Biomimetic Liver	Biomimetic Knees
Class 3 (2002-2006)	Bioelectric Fields	Bio-batteries	Biomimetic Hip
Class 4 (2003-2007)	Biomimetic Touch	Bio-photon Devices	Biomimetic Lungs

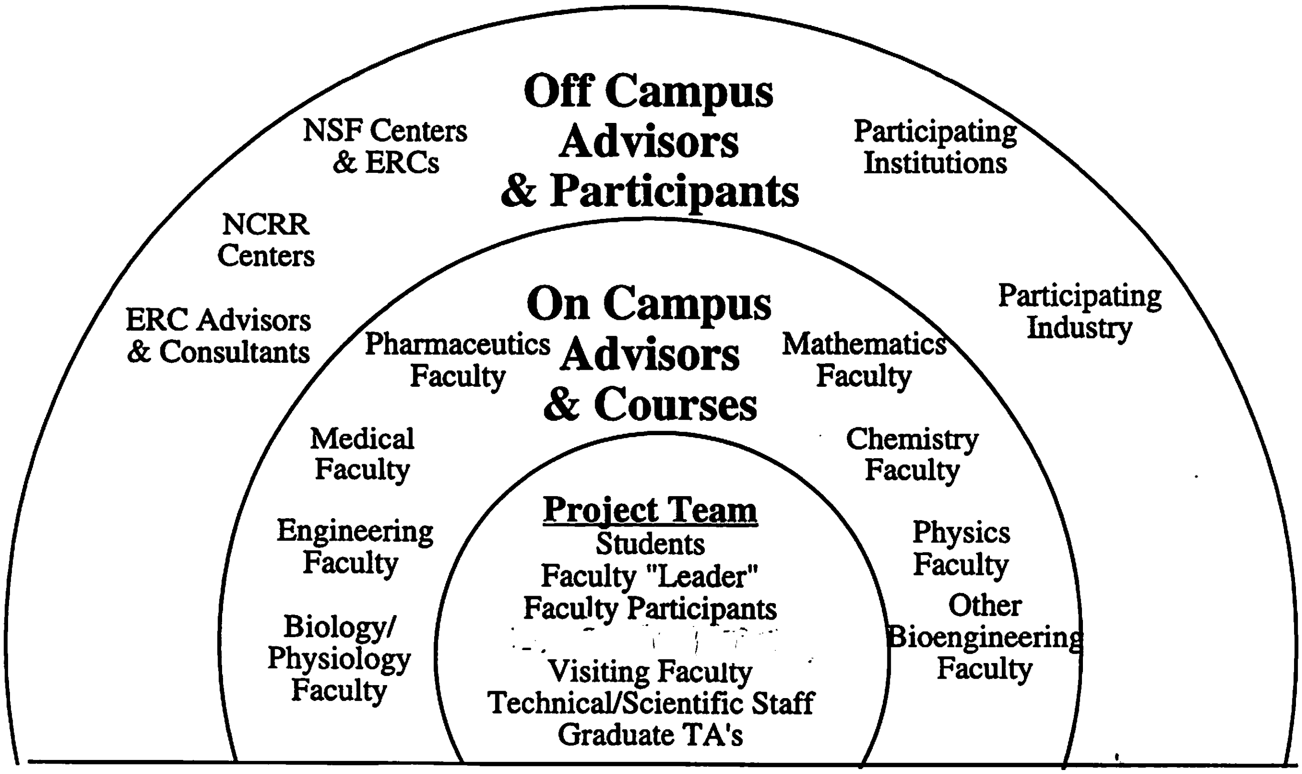


Figure 4. Typical project teams and resources. The central circle represents the Project Team, which includes the 5 to 8 undergraduate students and their faculty advisor. One or two additional bioengineering faculty and one to three faculty from other relevant departments will also be part of the team (they will be partially compensated from grant funds). Visiting faculty will also be team participants. Other paid team members and resources include technical staff and 1-3 graduate TAs.

Thrust 2: The "Living" Internet—The Web as an Experimental Tool (R. Rabbitt and K. Horch)

Large scale communication networks may be among the most complex man-made systems in the world. The multi-layered systems designed to control and manage information flow span multiple abstraction levels from physical signals and switching to service and business management software. Interestingly, the traffic and signaling in packet networks such as the internet show emergent, collective phenomena, including fractal network traffic patterns, that are not seen in single network elements. We see here very strong parallels to biological systems where interacting components, each of which operates on the basis of its own set of rules, give rise to emergent behavior and ultimately to behavior of the organism itself (2). Parallelism and redundancy are key components necessary for emergent behavior and for the ability to invoke self repair in the event of injury.

We will use the internet to study, learn and teach about biological systems. Our use of the internet will include powerful tools for information exchange.

We further propose to use the computer network itself as a physical model for biological signaling and communication, and to use individual computer nodes and their human operators as self-motivated biological components.

Student-faculty teams will work together using interactive software to study the behavior of biological systems via the collective basis of molecular, cellular, tissue, organ, systemic and organism level phenomena. These levels are not independent, but rather define a hierarchy of interactions that can usually only be understood by invoking higher and higher degrees of abstraction. Intracellular molecular cascades, for example, can be viewed on an individual component level and simulated as kinetic reactions taking place on individual computer nodes with time delayed signaling to related events taking place on other nodes. The inter-node communication implemented in this way is interesting in its ability to reproduce stochastic behavior on a local scale (molecular level diffusion and signaling), blurring on an intermediate scale (Fickian diffusion), and cumulative or distance related delays on a large scale. Beyond the molecular level, internet node-based activities can represent the macroscopic behavior of cells.

The internet is being applied to education at all levels. It has already revolutionized the exchange of data and information and the enhancements of collaborations and interactions in the research community. It has also been enthusiastically adopted by the elementary, junior high, and high school community, including national and even international projects (20, 21), such as the globe weather data gathering project sponsored by the National Oceanic and Atmospheric Administration, NSF, and NASA (www.globe.gov). The World Wide Web has also been applied as a distributed computing resource, allowing interested parties to participate in computational projects which otherwise would require relatively inaccessible super computer capabilities.

We will utilize the web for similar activities and projects, as well as for information dissemination and information acquisition. We will develop a practical and comprehensive web site for the project, for our own acquisition of information and advice as well as for dissemination of project deliverables and for the recruitment of students and participants.

Thrust 3: Multi-dimensional Visualization (S. Kern and K. Horch)

One of the difficulties in dealing with large, complex, non-linear interacting systems is obtaining a clear understanding of how such a system responds to different inputs and evolves over time, particularly in response to changes in its operating characteristics. Ideally one would like a method of visualizing the system that would work equally well on both a large (macroscopic) and small (microscopic) scale. The nature of the systems to be developed in the proposed projects are such that a mathematical description of the system, or even of significant subsets of it, would be sufficiently complex to preclude such an intuitive or conceptual understanding on the part of the students (or faculty).

Graphical representation and visualization of the system inputs, the states of its nodes (interacting components), and its outputs would seem to be the answer. However, each such parameter would represent a single dimension of such a representation, so a method of visualizing large multi-dimensional (such as hundreds) structures is needed (22). To do so, we propose to use a variation of a technique developed by a local company (nDV, LLC) founded by Robert Johnson, former chairman of the Department of Computer Science (see letter in Appendix A).

nDV has developed several new intellectual structures which provide n-dimensional graphical viewing to aid in understanding of structure and relationships in arbitrarily many dimensions. The techniques are visually intuitive and mathematically tractable.

nDV's version of Parallel Coordinate representation generates multi-dimensional display space images that look like overviews of mountainous terrain. As the system changes (for instance, in response to a new input), the terrain changes, and the evolution and propagation of this change is easily visualized at whatever scale the user desires.

We will also work with Dr. Dwayne Westenskow, Professor of Bioengineering and Anesthesiology, who is principal investigator on a project with Dr. Julio Bermudez from the School of Architecture. They are applying basic principles of 2D and 3D design (e.g., scale, shape, color, unity, etc.) and sound to produce "an interactive multi-sensory information system" that will allow us to more readily see and follow critical events in the functioning of the systems they have developed. The Bermudez/Westenskow approaches can (and will) be combined with nDV's parallel coordinates technology to further develop and enhance multi-parameter and hierarchical visualization.

Our institution has always been involved in computer graphics, scientific visualization, and computer art, beginning with the pioneering work of David Evans and Ivan Sutherland in the early

1960s. The Department of Computer Science is generally well recognized as a leader in computer graphics and in its application to scientific and engineering problems. We participate in a major NSF science and technology center titled the Graphics and Visualization Center, directed by R.F. Riesenfeld and E. Cohen (www.cs.utah.edu/projects). That Center includes a Scientific Computing and Imaging Group. Drs. Chris R. Johnson and Robert S. MacLeod are Bioengineering faculty involved in the Center, specifically in modeling and visualizing cardiac bioelectric potentials (29, 30, 34, 35). In addition, the new Center for the Simulation of Accidental Fires and Explosions (C-SAFE), funded primarily by the Department of Energy and directed by David Pershing, Dean of the College of Engineering, has major activities related to scientific visualization and multi-parameter, multi-dimensional data presentation (www.csafe.utah.edu).

We are well aware of the potential of the graphic arts, music, and even the performing arts in the analysis and presentation of scientific and engineering data and problems. Indeed, the Bermudez/Westenskow collaboration falls into this category. We have even integrated science, technology, and art into a unique liberal education science course for non-science majors (31). Through collaboration with our colleagues in the Graphics and Visualization Center and in C-SAFE, we are well aware of the rapid progress being made in enhancing scientific and engineering visualization of complex systems (32).

Thrust 4: Modeling and Simulation of Complex Systems (J. Wiskin and R. MacLeod)

> *"Formulation of such a mathematical model forces the modeler to identify explicitly the key components, the key reactions, the key interactions, and also to describe their quantitative interconnections. This exercise in systematic organization of assumptions and key features of the metabolic subsystem of interest can be a critically important contribution of the modeling effort to the intuition and insight of the researcher, almost independent of the consequences of the modeling calculations, The modeling exercise enforces a high level of intellectual rigor, careful study of prior work on the system, and systematic thought about its most important features.":*
>
> J.E. Bailey (38)

Modeling and Simulation are well known to bioengineering (16, 33). Indeed, bioengineers have made many advances and contributions in these areas. The various NIH-NCRR Simulation Resources (33) and other groups and labs have made very significant and important contributions, some of which are now being called mathematical biology (11-19). There is a growing interest in applying some of these methods and techniques in general undergraduate biology as well as in molecular and cellular biology (17, 18). We are fortunate that such programs and interests have evolved in our own Mathematics and Biology departments in recent years, including collaborative activities. This growing theoretical biology emphasis at our institution, coupled with Bioengineering's interest in the application of engineering modeling and simulation in our undergraduate and graduate curricula, makes this Thrust area timely and important.

The Departments of Computer Science, Chemical Engineering, Mathematics, and others are involved in major modeling and simulation activities. C-SAFE, described briefly in the previous section, is primarily a modeling and simulation activity. We will certainly collaborate closely with C-SAFE and apply their tools, interests, and expertise to bioengineering problems and opportunities. C-SAFE makes extensive use of the University's Center for High Performance Computing, as do Drs. Johnson and MacLeod for their studies on the modeling and visualization of bioelectric potentials for electrocardiology applications. In addition, the Graphics and Visualization Center, referred to briefly in the previous section, has as a major activity Computational Medicine, again represented primarily by the work of C.R. Johnson and R.S. MacLeod (29, 30, 34, 35).

The Departments of Pharmaceutics and other components in the College of Pharmacy are developing programs and interests in pharmacokinetics and pharmacodynamics. We also have a significant medical informatics activity in both the Computer Science and Medical Informatics Departments applied to molecular biology and human genome problems.

There has been a recent explosion of books dedicated to theoretical biology and its relationship to mathematics (11-15). It behooves the bioengineering community to continue to take advantage of, and to continue to contribute to, these abundant resources, and to use them to develop a balanced curriculum.

The students will be exposed to a succinct and accurate summary of the various analytic tools available, including both modern and more traditional mathematics. He/she will then be able to assess which techniques would be most appropriate to his/her project and interests. These will then be explored and developed in more detail.

Emergent order in complex systems is one unifying theme. Our approach to this paradigm is reflected in our motto and subtitle: Simplicity <---> Complexity ---> "Simplicity". This phrase is relevant not only to the actual operation of complex systems, but also to our appreciation and *understanding* of these systems.

The ECG is a good example, in which medical practice has been based on an almost empirical linking of disease state and signal features. A more appropriate and in the end much more powerful approach is to apply reductionist methods to deconstruct the ECG into component features (cardiac cells, coupled systems, volume conductors) and study the relevant behavior and features. The subsequent synthesis can then allow us not only to understand the features of the system we once observed empirically, but to see new things in those feature sets, and thereby improve both fundamental understanding and medical practice. Again from the ECG example, this has to some extent occurred in that we now can interpret, at least partially, the ECG in terms of fundamental sources and thus interpret more subtle features and pathologies. Examples of that include at least some ability to localize sites of myocardial infraction or initiating events in some cardiac rhythm disturbances. So the ability of the SCS approach is to both improve our understanding of high level data we already collect and use, as well as make these data effectively richer in content and value.

The purpose of simplified models is not to attempt to explain everything, but rather to isolate or 'abstract' those particular elements of the process being modeled that are relevant to the understanding of a particular behavior exhibited by the system (2, 17, 18).

Nonlinear systems are prevalent in biology and thus in bioengineering. Such systems exhibit hysteresis, catastrophes, bifurcations, chaos, resonance, fractal dimension, entrainment, self-sustained oscillations, and quasi-periodicity. All are important in understanding, controlling, modifying, and engineering biologically based systems.

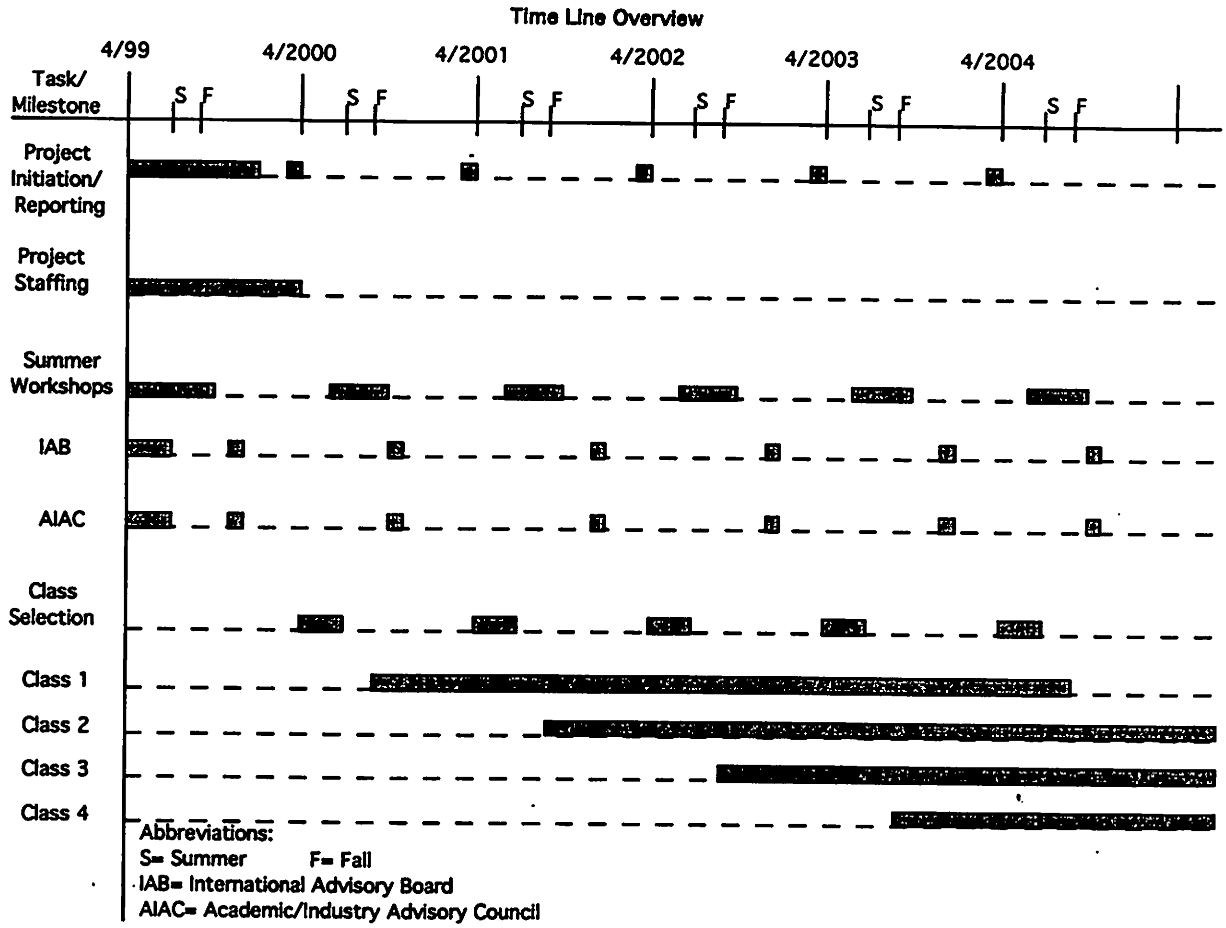
An overview Time Line for the ERC's first five years is given on the next page. We will rapidly implement the Executive Committee and the Bioengineering Summer in Utah Advisory Committee to begin organizing the high school summer program. The technical and administrative staff will be hired and on site shortly after funding is available. As soon as we know there is a high probability of receiving the award, we will initiate a search for those individuals, so that committments can be made shortly after startup.

The Time Line shows the schedule for class selection and the class start/finish dates for the first five years of the ERC.

We will also meet via phone and E-mail with both the IAB and the AIAC to obtain their collective inputs early in the project. Their first joint meeting will be in Fall, 1999, to review the first summer program and to review our plans for the projects, courses, and research projects.

E. Deliverables

Our initial deliverable will be a set of projects for the first class of students, as well as a set of smaller projects to be used in the high school summer workshops. The four year integrated curriculum projects will be developed during the first 14-15 months of the grant and will be applied with the first class in the Fall of 2000. Other deliverables will include: a means of organizing, staffing, and conducting such a complex integrated project and means to efficiently provide needed resources and analytical tools. The deliverables will also include a set of special courses designed



to optimally interact with and support the integrated projects. One course is Measurement and Medicine, an introduction to quantitative biology, physiology, medicine, and pathology, and will provide the students with a comprehensive perspective of living systems, the basic principles and concepts of biology, and the challenge of parameterizing and quantitating biology, pathology, and medicine. The first semester of this course will focus largely on normalcy, i.e. normal biology and physiology, whereas the second semester will focus on abnormality, i.e. pathology and medicine. This course has been in the conceptual design stage for the last year as a joint project of Professors Andrade, Horch, and Kern. Its development will be a major effort of the first year of the project.

Professors Rabbitt and Christensen are developing a new freshman bioengineering course for our new (1999) undergraduate curriculum. Their freshman sequence in undergraduate bioengineering applies fundamental laws of physics and chemistry to the analysis of biological systems and to the design of biomedical devices. Diffusion and molecular transport, electrochemical gradients, heat and mass transport, and related topics are used to explain some of the basic principles of cellular, organ, and systemic physiology. The same tools are also applied to the design of biomedical devices such as the artificial kidney and neuroprosthetic devices. The course consists of three lectures and one laboratory session each week. Lectures are unified around the theme of flux laws and conservation laws with motivation and applications derived from biology and biomedical engineering. Freshman calculus will be taken concurrently. This course will also be taken by the students in this project-based program.

Other specialized courses and short courses will evolve and develop during the conduct of the projects themselves (see Section F). These will also be "deliverables" and will be available on the web site for access by the larger community.

The web site itself is also a "deliverable" in that information on the design, organization, utilization, and general evolution of the web site will be available for those interested in developing and constructing other such sites. We will work closely with the Center for Advanced Instructional Media at Yale University (Carl Jaffe, Director) in the design and development of such a site as well as its use for the assessment of our projects, courses, and general project activities by the larger community (see Section I, Assessment and letter in Appendix A).

We will develop a set of tools in a range of areas, utilizing existing experience, technology, and analytical tools as much as possible. This will include a methodology for the analysis, reduction, and simplification of complex biological and bio-based systems, what we might call reductionist tools. Much of this is already in place in the literature on theoretical biology and on modeling and system simplification (11). These tools will evolve from our project experiences, as the first year of each project will devoted to simplifying it into a set of basic components which can be modeled, simulated, constructed, tested, and evaluated.

We will also develop a set of synthesis tools, again using the existing literature and experience, but deriving from our particular experience in the projects. These will begin to evolve in the second year of the class projects, as the teams take the components of their complex system and begin to assemble them into subsystems, the synthesis approach. The means by which these subsystems are mentally assembled and modeled, the construction of operating subsystems, and their analysis and assessment will all be part of the synthesis tool kit. We will develop means to view the assembled subsystem and overall complex system in a hierarchical manner, i.e. from different perspectives, with the eventual goal of obtaining the new "simplicity" derived from the hierarchical analysis of this now complex system.

Each of the major research thrusts in the program will also develop a tool kit specific to that thrust area:

The "Living" Internet as an Experimental Tool
Multi-dimensional Visualization
Modeling and Simulation

We will of course integrate the kits. Two biology-based "tools" are of particular interest. There are two key biological concepts which are largely unknown to practically all engineers and indeed to practically all non-biologists. One is <u>Darwinian evolution</u>, which one might simplistically view as survival weighted combinatorial science and engineering. The second such area is <u>embryology and development</u>—the means by which incredibly complex organisms can result from essentially a long string of linear information (53). These two basic biological concepts have rarely been treated as such in bioengineering education. Appropriate understanding of such basic concepts are likely to dramatically change how we approach many bioengineering problems and opportunities.

The Department's goal is to produce a unique undergraduate bioengineering experience which also challenges and enhances the graduate program. We want to produce student, faculty, and other participants who are comfortable with complex bioengineering-based problems, but in addition have the communication and leadership skills, and the community and societal interests, to select important and relevant problems and to help garner the resources to permit such problems to be successfully addressed. Although we do not anticipate a very large undergraduate or even graduate program, we do anticipate that those people products from our programs will effectively disseminate the philosophy, activities, approach, and tools.

This project is entirely consistent with the Department's long range goals. J. Andrade, the PI, is Co- Chair of the Department. K. Horch, who leads two of the key thrust areas, is also Co-Chair of the Department of Bioengineering. The development and implementation of our new undergraduate program was encouraged, even pushed, by our then Dean of Engineering, David Pershing, now the Executive Vice President of the University of Utah. Our new President, Bernie Machen, is deeply committed to the enhancement of interdisciplinary education and research. He is also deeply committed to significant enhancement and improvement of undergraduate education at the University of Utah. Our Vice President for Research, Dr. Richard Koehn, is himself a bioengineer, having directed a major biotechnology center at the State University of New York prior to his appointment as VP for Research six years ago. There is strong commitment at all levels for this program.

The bioengineering community has grown and developed dramatically in recent years. There are many more departments and programs, in large part fueled by the Whitaker Foundation's Special Opportunity and Departmental Development Awards. There has also been a considerable development and expansion in what is called Biomathematics and Quantitative Biology. Indeed, we feel that Gilbert Chauvet's three volume treatise, Theoretical Systems in Biology (11), together with the other works previously cited (12-19), will launch new directions and approaches in both biology and medicine. This may be helped the Whitaker Foundation's Teaching Materials Program, which is striving to induce the community to provide an integrated, quantitative, engineering approach to basic biology to aid the education of the next generation of bioengineers.

We feel that the bioengineering community, the biology and mathematics communities, and even the medicine and clinical communities are ready for, indeed anxious for, the programs, courses, projects, and tools which we propose to develop and evolve. Although effort is required to disseminate the materials and to inform and involve the community at large, we feel this will be the easiest part of the project, as the community is eagerly receptive to such activities and developments (36, 37).

F. Research Program

Thrust 1: Bio-Based Integrated Projects

"It is not the answer that enlightens but the question."
Eugene Ionesco (65)

"Students respond enthusiastically to their first taste of science or engineering in a research or design project. Their book learning suddenly comes to life, and they discover talents they never realized they had. Scientists known only as remote instructors often become mentors, colleagues, or even friends." (58)

Integrated bio-based projects are the key to our approach to bioengineering education and to the application and development of technologies for the enhancement of bioengineering education. The projects have been discussed in earlier sections. Table 2 summarizes key criteria for the selection and development of the projects.

Table 2. Project Characteristics and Needs (see also Figures 2-4)

Complexity:	Must be sufficiently complex to require hierarchical and complexity analyses and to exhibit non-linear, emergent properties.
Reductionable:	Must be reducible to a set of subsystems and a larger set of primitives or components, many of which can be easily analyzed, constructed, and tested.
Synthesizable:	Primitives or components can be combined and assembled into systems which begin to exhibit complexity.
Bio-based:	Must involve sufficient biological knowledge and concepts to serve as a means of learning biology and doing "bio-based" engineering.
Practical:	Must be applicable to one or more areas of medicine, industry, or to other societal needs or problems.
Relevant:	Must be of interest to project team and thus serve as a pedagogical tool for motivation and involvement.
Intellectual Resources:	In house, on campus, and more extended intellectual resources (Figure 3) must be available.
Material Resources:	Must not require overly expensive tools, materials, equipment, or specialized, expensive services.
Safety:	Must not involve any unreasonable or inappropriate risk or hazard to those involved.

Although the make up of a typical project team was illustrated briefly in Figure 3, Table 3 provides more complete information.

Although our institution and College has considerable undergraduate project experience, most of it is for limited or short term projects. An Engineering Clinic, directed by Electrical Engineering Professor M. Iskander and sponsored by industry, utilizes a set of short team-based projects and is effective. There is a senior design project requirement in the Department of Mechanical Engineering. The Department of Materials Science has a senior thesis project, essentially a capstone 12-18 month project. The only group on campus affiliated with engineering that has such extensive long range projects is the Center for Engineering Design (CED), originally the Center for Biomedical Design, founded and directed by Dr. Stephen Jacobsen in Mechanical Engineering and Bioengineering. But CED's objectives are somewhat different. The students are involved in projects for various research and development sponsors, and, although in many cases students were involved for multiple year periods, they were generally hired to provide services on a sponsored project. Although these projects did often tie to course work and involved laboratory/project based credits, they again served a different overall need. Dr. Jacobson is our most experienced faculty member when it comes to engineering projects related to those we are proposing to develop and implement. He has agreed to serve on our advisory board and will play an important role during the first several years of the program in helping to assess and evaluate our project development and implementation activities (Appendix A).

Table 3. A Typical Project Team

Students (5-8)	Selected from the project-based entering class after about 3 months of exposure to all projects. Team assignment based on interest, motivation, background, and project balance. Each team will select a team chairperson, organize into subteams and tasks, and work with faculty to select and involve other team members.
Faculty Advisors (3-4)	A faculty resource team will initially design and develop the project prior to presentation to the class and prior to the selection and formulation of the student team. Faculty will have expertise and interests in the project topic and will generally commit to the project for the entire 4 years. One faculty member will serve as key or principle advisor to the team. This position may rotate among the faculty team each year. The principle faculty advisor will likely spend ~ 10 hours/week/team. Other faculty will each spend 5-10 hours per week per team. They will be compensated for this work.
Visiting Faculty (0-1)	Visiting faculty are budgeted and will give lectures, short courses, and be directly involved with the teams. Visiting periods range from 1 day to one semester. There should be 2-7 visiting faculty per year, depending on resources. These faculty will also be available via the Internet and by telephone.
Graduate TAs (1-2)	Graduate TAs will be second or subsequent year graduate students working in an allied area. They will spend up to 10 hours/week/team and be compensated for their services. They will be evaluated by the undergraduate team members and retained or released based on their usefulness to the project.
Technical Staff (1-2)	Technical staff will be hired by the ERC specifically to assist with the projects. We expect 1-2 design/prototype engineers, 1-2 biologists, and 1-2 physicists-chemists, and 1 mathematician. These will be "allocated" to the 3-12 projects based on need and time available. These will be MS/ME level individuals, generally with substantial industrial and/or lab expertise. One staff person with both administrative and technical skills and interests will manage and "run" the special projects laboratory and stock room.
Others (0-1)	Retired and other individuals with appropriate experience will be recruited as volunteers. Visitors from industry will also be involved.
Total (~ 10-15)	

Dr. Robert Romer, Chairman of the Department of Mechanical Engineering (ME) and Coordinator of ME's senior design activities will also serve as a key project advisor, as will a number of our industrial representatives and participating institution representatives, particularly Dr. B. Onaral, Chairman of the Bioengineering Program at Drexel University, because of Drexel's strong commitment to project-based undergraduate education in their College of Engineering (Appendix A).

Project A: Neuromimetic Systems: Vision (R. Rabbitt, Faculty Advisor)

> *"Although human genius through various inventions makes instruments corresponding to the same ends, it will never discover an invention more beautiful nor more ready nor more economical than nature because in her inventions nothing is lacking and nothing is superfluous."*
>
> Leonardo da Vinci

INTRODUCTION

Across the animal kingdom one can identify common design principles that appear to be fundamental and perhaps salient to the success of all life on earth. On a low level nature routinely employs elemental redundancy, self organization and self assembly. And on a higher level sensory fusion, hierarchical control, and adaptive plasticity are common if not universal themes. The potential for application of these basic principles to solve engineering problems is immense. It is this promise that underlies recent trends towards biobased and biomimetic systems.

One of many elegant biological designs is the human visual system. The foveal region of the human retina spans only 4% of the retinal surface area yet it contains a majority of the sensory cells (about $7x10^6$ cones and $100x10^6$ rods). Since resolution of the peripheral region of the retina is greatly reduced relative to the fovea, we articulate our eyes within their orbits to focus visual targets on the high-resolution foveal region. This multi-resolution design strategy greatly increases the acuity of selected regions of the visual scene without the massive increase in information content that would come with spatially homogeneous sensors, such as standard rectangular CCD arrays. Machine vision would benefit from application of this biological approach. To engineer such an apparatus it is necessary to have in place systems to accurately control the motion of the articulated visual sensors -- one that can accommodate head motion, target motion, unexpected changes in the environment, and/or system degradation. The human ocular control system achieves exactly this. This system exhibits motor learning, draws from a multiplicity of sensors (vestibular, ocular, somatosensory), activates a multiplicity of actuators (extraocular muscles, neck muscles, autonomic system), employs a hierarchical control strategy (peripheral, brain stem, cerebellum, cortex), and invokes multiple feedback loops between each of these subsystems (central and efferent).

OBJECTIVE

Our primary objective is learn how the visual system achieves its remarkable multi-resolution acuity and to express these same design strategies in a biomimetic machine vision system. To accomplish this goal we must study the biological system and develop a quantitative understanding of the biological sensors, actuators and control systems involved. The engineering challenge is to identify/design devices to mimic the salient function of each biological component and to implement a control system capable of accommodating system degradation and/or changes in the environment in a manner which mimics biology. Your goal as a student is to develop the skills necessary to meet this challenge and, ultimately, to construct a functional biomimetic vision system. This challenge has been framed as a series of laboratory projects outlined below.

LABORATORY PROJECTS

Freshman Year

Psychophysics of vision.

- Perception of intensity, color and spatial resolution.
- Compare visual performance to CCDs and vacuum tubes.
- Optical illusions.

Optics.

- Geometrical optics. Huygens' principle and refraction. Fermat's principle.
- Camera optics. Role of the aperture and shutter.
- Optics of the eye. Cornea, lens and pupil.

Optical flow computations and the retina.
Computational optical flow algorithms.
Hard-wired optical flow sensors.
Construct an optical flow sensor.

Neuronal computations

Visual processing of form, color and motion.
Neurons and the computational brain.
Central pattern generators and small networks.
Program a large-scale associative neural network for pattern recognition.

Senior Year

Neuromimetic control

Feedback control and neural reflex systems.
Redundant pathways.
Sensory fusion.
Motor learning in neural systems.
Experiments to modify vestibular-ocular interactions with magnifying/minifying goggles.

Senior project

Build a biomimetic vision system with the following features:

- multi-resolution "foveal" optical sensor,
- articulation system to allow for target tracking, movement compensation and saccades,
- optical flow and gravito-inertial sensors for feedback control,
- neuromimetic feedback control to maintain targets on the foveal sensor and
- video display of captured images.

SUMMARY

Robotic implementation of an articulated biomimetic vision system has never been attempted before. Your work will have important applications in areas such as machine vision, biorobotics and tele-robotic man-machine interactions. Present machine vision technologies do not stabilize images in the presence of sensor motion, are poor at target tracking, do not have multi-resolution acuity and fall short of providing the appropriate man-machine interface for haptic or tele-robotic applications. Your biomimetic vision system will speak directly to these engineering challenges.

Project B: Engineering Bioenergetics (J. Andrade, Faculty Advisor)

"If you want a quantitative answer, you must ask a quantitative question."
H. Kacser (49)

INTRODUCTION

Our chemical and biochemical genealogy go back nearly four billion years to the most primitive life forms. These ancient anaerobic reactions likely constitute the oldest part of our personal biochemistry. Much, much later, after the evolution of photosynthesis dramatically changed the environment, an aerobic bioenergetics evolved, leading to highly efficient means to fuel and power life. We are among the beneficiaries of that four billion year old combinatorial, chemical genealogy. Our personal biochemistries, albeit complex, are very similar, but not identical. We are biochemical individuals (52), just as we are unique in features and character.

We wish to understand our personal biochemical individualities. We must be able to measure it. We often need to modify it, due to abnormalities or perturbations which are undesirable (diabetes, phenylketonuria, liver disease, etc.). We may wish to engineer the biochemistry of an organism to enhance a particular biotechnological process. We may need to grow specific tissues under non- "natural" conditions (tissue engineering). We may want to enhance our own physical performance (diet, nutrition, and conditioning). We may wish to perturb—to slow down—certain aspects of aging, related to changes in metabolism and thus to the need to optimize diet and nutrition.

We may also want to become inspired and stimulated by nature's bioenergetic processes, in order to synthesize chemicals and fuels from the air itself—from CO_2 (the dark side of photosynthesis), using only solar photons as energy (the light side). We want to engineer efficient energy storage and energy transformation devices (bio-batteries? fuel cells? "artificial" chloroplasts?).

Metabolism is a very complex interacting chemical network—a complex system. Much of metabolism and enzyme biochemistry is resolved and mapped, what Koshland calls "The Era of Pathway Identification" (49). By the early 1980s extensive work led to "the Era of Pathway Regulation." Koshland says we are now entering "The Era of Pathway Quantification." We now have tools such as metabolic control analysis (42-48). The complex biochemical network charts found in biochemistry textbooks are being modeled and analyzed. Their complexity, typical of complex systems, is yielding to a fuller understanding—to a new "simplicity".

OBJECTIVE

Our immediate (four year!) practical objective is to design and develop an artificial liver (50, 51). But a deeper objective is to be able to design, apply, and "build" biochemical processes and systems ranging from "simple" biosensors to "complex" livers. The simplicity and complexity of biochemistry are critical keys to the understanding of life itself.

LABORATORY PROJECTS (tentative)

Freshman Year

Laws of conservation and thermodynamics—Physics rules!
    mass and energy balances
Chemical reaction principles—Chemistry builds!
    equilibrium, activation energy, catalysts
Multiple and driven reactions—"Beating" entropy!
Evolving prokaryotes— "Simple" cell bioenergetics
Evolving eukaryotes— "Complex" cell bioenergetics
    dinoflagellates, photosynthesis, respiration
Anatomy of bioenergetics
    mitochondria, chloroplasts

Sophomore Year

Biomacromolecules—Good-bye to chemical "simplicity"!
Enzyme and reaction engineering
Modeling coupled reactions
Heterogeniety of biochemistry—Welcome to surface and interfacial chemistry!
More anatomy of bioenergetics
Biosensor design and development
Drug and nutrient delivery devices
Beyond dinoflagellates

Junior Year

Coupling of biochemical modules
Channeling
Bioelectronics—electron and proton fluxes
pH, potentials, and ion fluxes
Multiple enzyme reactions and cascades
Amino acid synthesis
Control and regulation

Liver cells, tissue, and structure
Extremophilia

Senior Year

Multichannel biosensors
Feedback controlled release and delivery
Protein design and engineering
Mammalian bioenergetics and obesity
Aging, nutrition, and sensors
Coupled bio-synthetic systems—biochemical engineering
Bio-batteries
Artificial liver

SUMMARY

It's been a long, busy, productive, motivating, and educational four years. We now have an understanding of and experience with the chemical bases of living systems. We know how to perturb, control, regulate, and engineer biochemistry. We have ideas for biochemistry-based devices and processes which are probably unique and highly creative. We are now project-based, hands on, chemically confident bioengineers On to other problems and challenges!

Project C: Cardiomimetic System (very tentative) (G. Pantalos and S. Kern, Faculty Advisor)

INTRODUCTION

Another elegant biologic design is the cardiovascular system. In its simplest representation, the heart is a pump responsible for fluid delivery within the body. However, unlike most pumps, it modulates its output based on upstream and downstream loading conditions, the presence of chemical agents within the fluid stream that alter the loading conditions and the pump function itself, and by direct signals created from neural pathways. These mechanical, chemical, and electrical inputs all serve to regulate power from the pump in unique ways. To mimic this system requires the ability to dynamically respond to multiple sensory inputs to adapt the rate, stroke volume, and force generated by the pump to meet the metabolic demands of the organism. Like the visual system, this system draws from a multiplicity of sensors, activates many actuators, employs hierarchical control and uses multiple feedback loops, some of short and some of long time constants, to achieve its means.

OBJECTIVE

The primary design objective of this project is to understand how the cardiovascular system achieves its dynamic range of function and how that range can be mimicked by an engineered system. The engineering challenge is to design a biomimetic system of cardiovascular function and compare and contrast your system with those developed as ventricular assist devices, artificial hearts, and coronary bypass machines.

Freshman Year

Functional Cardiovascular Control

- blood flow through the cardiovascular system
- segmentation of the heart
- role of valves and flow control
- bipump balance
- fluid balance within the system, within regions

computer aided design of pump
fabrication and initial functional testing

Junior Year

Ventricular energetics
- conduction/convection/radiation principles
- energy balance within the heart
- thermoregulation in the body
- functional thermodynamics

Cardiopulmonary interactions
- diffusion principles
- membrane physiology
- elastic coupling between chest, lung, and heart
- pressure/flow relationships in oxygenation and ventilation.
- cardiac interactions

Sensors
- pressure sensing and impact of cardiovascular muscle
- flow sensing and impact on oxygen content
- measurement of low concentration substrates
- integrating a biomemimetic control system

Feedback control
- physiology of cardiovascular control
- systolic versus diastolic function
- endogenous substance impact on the cardiovascular system
- designing control rules for multiple feedback sensors

Senior Year

Cardiomimetic control
- understand the physiologic interrelationships between biomechanical, biochemical, and bioelectrical phenomenon that alter cardiovascular function in terms of pressure and flow.

Integrative project
- build a cardiomimetic fluid delivery system that responds to changes in preload, afterload, oxygen and carbon dioxide concentrations and concentrations of specific endogenous analytes such as sympathetic amines.

SUMMARY

Development of a fully operative cardiomimetic system that responds to pressure, flow, and biochemical alterations in the fluid being delivered (blood) represents an extremely challenging project with implications in many areas outside of bioengineering. This concept AND comparison to artificial heart systems and temporary bypass devices will highlight the functionality of the cardiovascular system as a dynamic pump.

Thrusts 2-4: Common Aspects

The "research" in this application is defined differently from that in a normal NSF grant. This ERC application is focused on education. Our "research" here is to develop tools, methods, resources, and programs to enhance bioengineering education at both the undergraduate and graduate levels.

Thrusts 2-4 have common objectives and goals: to develop, apply, and continue to improve and enhance a set of "tools" which will aid students in the study and understanding of complex subjects and systems—efficiently and effectively. We do not wish to reinvent "wheels" which already exist. Thus we will thoroughly and completely determine and assess the tools which already exist, many of which are developed and used by scientists and engineers in their research and for graduate education. We will test and evaluate these tools using the data sets, systems, and subjects appropriate to our complex, integrated, bio-based projects. The useful tools will be modified, improved, and enhanced as required.

Thrusts 2-4 are budgeted most heavily in Years 1 and 2, with the goal that by Year 3 the tools will be largely developed and will be applied by the students, faculty, and staff in the respective projects. Funding in Years 3-5 is to test and improve the tools. Our participating institutions will also be involved in tool development, testing, and evaluation, as will the industrial participants.

Key faculty involvement in the four research thrusts are summarized in Table 4.

Thrust 2: The Living Internet: The Web as an Experimental/Analytical Resource

We said in Section D that

> "Student-faculty teams will work together using interactive software to study the behavior of biological systems via the collective basis of molecular, cellular, tissue, organ, systemic, and organism level phenomena."

This is easy to say and very hard to do. The exponential expansion of information technology both creates and demands an expansion of our knowledge of the nature of information. Information networks may be among the most complex and fastest growing man-made systems in human history. Interestingly, information networks and their use patterns are similar to biological systems. At a low level, traffic and signaling in packet networks such as the internet show emergent, collective phenomena, including fractal network traffic patterns, not seen in single network elements. Likewise, overall network behavior does not originate centrally nor is it centrally coordinated. It cannot be explained by technical details of infrastructure, hardware or software alone. Instead, these structures parallel biological phenomena, in that interacting self-autonomous components give rise to emergent behavior, spontaneous self-organization, and self-repair. Informational relationships become as important as physical and material ones in the network.

Tools traditionally used to study biological systems could be used to understand the behavior of informational structures, through all levels, from the single node hardware, the interfaces to the network, the network itself, and, ultimately, the different 'agents' using this system. Likewise, treating informational structures as expressions of biological phenomena could enhance the understanding and knowledge of biological systems.

In the context of this proposal, the internet will serve two purposes. First, it will provide the informational infrastructure serving the intra- and inter-project communication needs. Projects pursued by the student-faculty teams, while designed to be stand-alone, do revolve around a common theme of simulating biological systems. Ultimately, these different systems will be interconnected into a whole biological organism. This will necessitate communication between the project teams to exchange information about system-to-system interfaces, contexts of simulated biological behavior, data and signals generated from each individual system.

Initially, project members will communicate with each other and with members of other projects. As the projects mature, software and hardware interfaces will be developed, through which the modeled and simulated organ systems communicate. Additionally, the internet will be used in the lectures, outreach efforts, and administrative coordination aspects of the grant. Collaborations with other institutions on other campuses will be added to and become part of the informational structures growing around this grant.

Table 4. Key faculty involved in the four research thrusts.

Key Faculty	Thrust 1 Projects	Thrust 2 Living Internet	Thrust 3 Visualization	Thrust 4 Simulation
Andrade, J. biomaterials, biossensors, biochemistry	X		X	
Christensen, E. electrical eng. optics biosensors	X			
Frazier, B. instrumentation electrical eng.	X			
Hlady, V. physical chem. biomaterials	X	X		X
Horch, K. instrumentation neurophysiology	X	X	X	
Johnson, R. computer science mathematics			X	
Kern, S. anesthesiology instrumentation	X	X	X	X
MacLeod, R. computer science mathematics			X	X
Pantalos, G. biomechanics physiology	X			
Rabbitt, R. biomechanics sensory physiology	X	X		X
Trujillo, E. biochemical eng	X			
Westenskow, D. instrumentation anesthesiology			X	X
Wiskin, J. mathematics				X

Second, this growing informational network, which uses the internet as its infrastructure, will serve as a 'petri-dish' in which the biological phenomenology of communication networks can be studied. The informational structure surrounding this grant is expected to be very plastic and will go through different phases, paralleling that of the grant itself. As project structures change, the informational structure will go through periods of renewed growth and degeneration. Close

Thrust 3: Multi-dimensional Visualization

"Strange! I don't understand how it is that we can write mathematical expressions and calculate what the thing is going to do without being able to picture it."

R. Feynmann (66)

A simple but highly useful approach to multi-dimensional "visualization" is the use of spider or star plots utilizing radial, polar, or even spherical 3-D coordinate systems to present multi-dimensional data (23-26). We have used this in a preliminary way to simplify and to visualize the complexity of protein interfacial reactions (23). We are now using it as a means to present multi-parameter clinical chemistry data so that the visual pattern generated by the locus of points on the spider plot is designed to reflect particular disease states and metabolic conditions (24-25). Although such plots are incorporated in some plotting and graphical analysis packages and software, and widely used in certain specific fields such as sensory assessment (26), they have not been widely applied in most other areas of science. There has been limited use in clinical medicine, demonstrating that such approaches have enormous potential (24). There are many other very effective means of plotting and presenting data, including n-dimensional data (27-28), but which are not really widely applied.

The n-dimensional parallel coordinate approach from the local firm, nDV, was briefly described earlier. nDV-Explorer is a set of new intellectual structures for analysis of relationships of multidimensional data using Parallel Coordinates. Parallel Coordinates are used to allow representation of arbitrarily many dimensions (parameters) or coordinates, allowing one to "see" in many dimensions using a proper display space model.

Of particular interest to our application is their display space model, viewed using 3D virtual reality techniques, and capable of showing multiple instances (experiments) superimposed or in adjacency. They also have a directrix technique for mapping geometries back and forth between orthogonal and parallel coordinates. This provides the basis for curve fitting, modeling the data in each coordinate for extrapolation or interpolation, coordinate transformations, and understanding the relationships between the many coordinates. They also note a new "dimension" to functional analysis, in that the data models show that there are finite-difference slopes that are important in the data spaces, but that are not defined in classical functional analysis.

This is a good case of building on an existing technology which will likely be commercially available in the next several years. By becoming involved with nDV at this early stage, we can provide data sets, challenges, and other motivation to help them produce a product highly useful for bioengineering education.

Visualization is also a popular and productive activity in the radiology and medical imaging community. We will involve our local bioengineer/medical imagers and our other collaborators in discussions to quickly and efficiently learn what is available in their communities. The whole issue of perception of these visualization tools is critical—a subject also of interest to medical imaging (54).

We have just learned that C. Johnson and R. MacLeod will likely soon receive an NIH grant from the National Center for Research Resources for a center for Bioelectric Field Modeling, Simulation, and Visualization. This will be discussed in the next section. The relevant part from their proposal for this section is:

> "Another category of computer applications is scientific visualization. Visualization is an essential component of virtually every bioelectric field problem and provides a means for viewing geometric models, experimental results, simulation results, and clinical observations. For example, to visualize a three-dimensional head model along with the MRI scans from the patient and the results from a source localization simulation would require the integration of many different types of visualization techniques—visualization of the geometrical mesh, visualization of the MRI data using volume rendering, visualization of the shading—integrated into a single frame."

Although their work is focused on research and graduate education applications, we will work closely together to simplify and transfer those tools and methods which are appropriate to our visualization needs.

We are interested in very simple ways to illustrate and help understand complex phenomena, hence our interest in working with artists (noted in Section 4), cartoonists, etc. In the words of Martin Kemp and Richard Feynman (66):

> "Feynman diagrams look superficially like the simple graphics that physicists have uses for centuries. But they are devices of exceptional power. Within their space-time coordinates, Feynman was able to sidestep the long winded algebraic formulas that treated electrons and positrons separately. All the equations came together in one picture in a way that preceded and even directed calculation.
>
> The diagrams mirror his conviction that **"there is...a rhythm and a pattern between the phenomena of nature which is not apparent to the eye, but only to the eye of analysis".**
>
> Such a potent grammar of diagrams and matching equations provides a marvelous tool."

Thrust 4: Modeling and Simulation of Complex Systems

> *"Much has still to be done towards the elaboration of an integrative physiology, i.e. a formalised general physiology. This would call for the development of novel mathematical methods, the interpretation of experimental results, and the construction of appropriate models inspiring further experimentation. Instrumental and technological advances are today producing vast amounts of highly refined data which are far too scattered to be readily encompassed. A formalised integrative physiology may be expected to rationalise this extraordinary diversity of information within a sound theoretical framework, thus contributing to a deeper insight into the wonders of the living organism."*
>
> G. Chauvet (11), Vol. 3, pg. 626.

A key aspect to the project based curriculum is the ability to simulate and model physiologic systems and subsystem components. To do this, we will assemble and develop a toolbox of simulation algorithms, subroutines, and methods to support the individual projects. A significant core set of tools will be available and used for all the projects in the curriculum. Also, tools specific to each project will be developed or assembled from existing sources to augment the simulation aspect of each project. Students will complement a traditional curriculum in mathematical foundations, including calculus, linear algebra, and matrix and vector calculus, with these applied tools for solving aspects of biologic problems.

An emphasis of these tools will be towards solving non-linear problems due to their ubiquity and importance in biologic systems. Though non-linear systems are typically approached using numerical methods, we will use exact and "almost" exact solutions based on ordinary and partial differential equations. Usually the first inclination is to linearize these problems to solve them. Instead we will focus on simplifying models to analytic and semi-analytic solutions. These simple models can then be evolved to more complex models by increasing dimension or parameter space. Finally, simple models and control strategies are abstracted from the complex models. In this manner, the toolbox and teaching methods will support the Simplicity → Complexity → Simplicity theme of this proposal.

During the first two years of this project, significant effort will be devoted to assembling and developing the algorithm toolbox. Following this initial effort, the focus will shift towards implementation of these modeling and simulation tools, adaptation of tools for specific projects, and assessment of their utility for iterative modification as the project based curriculum is continually refined. We will address the following specific aims:

1. Assemble and develop a toolbox of algorithms for modeling and simulation of physiologic systems as examples of classical engineering concepts.

We will begin by searching the Internet for a broad spectrum of codes and subroutines which are available for public domain use. A large list of bookmarked sites with valuable subroutines and algorithms will be compiled after these routines have been evaluated and used by project staff. Methods and routines which are not readily available will be further investigated through published sources of software code. Finally, the project staff will write subroutines for use by the student for those critical tools that are not available in a form which suits the project based curriculum.

The focus in creating this toolbox is to make available to the student algorithms which can be conceptually explained in brief terms and readily applied once the conditions of the algorithm's applications are understood. A goal of the toolbox is to provide as many different methods for solving similar problem types so that the students can compare the advantages and shortcomings of different approaches based on the results each produces to a common problem. It is our belief that many techniques can be fruitfully applied even if the detailed theory of the method is not known. There are a large number of techniques that are not covered in elementary courses because to address them "properly" requires more knowledge than is generally available to beginning engineering students. However, it is possible to communicate the fundamental ideas of many techniques and *see them applied* to biologically relevant systems in order to supplement their comprehension. The important aspects of theorem proof can then be left to more formal math classes.

2. Create introductory and follow up classes to present the mathematical toolbox concepts developed in Task 1.

There are rarely closed form solutions to linear or nonlinear models that arise naturally in biology. However, there are many techniques available in mathematics and physics literature which give closed form or almost closed form solutions to ordinary and partial differential equations. This course would be an introduction and overview to the full spectrum of mathematical techniques; exact, approximate, and numerical; available for engineering problems. These techniques would be highlighted through the toolbox functions created in task 1.

The introductory class would cover two semesters and would have two course teachers who would be responsible for curriculum implementation, administration of the class effort, and roughly half of the teaching (initially MacLeod and Wiskin). The remaining portion of the class would be taught by the individual instructors responsible for each project in the project based curriculum. The class would begin in the 2nd semester of the freshman year for bioengineering students and end after the 1st semester of their second year.

The course will unify and enumerate many techniques that are useful in applications. The underlying theory will be minimally considered not because of its lack of importance, but to allow students to be exposed to a broad range of mathematical and simulation techniques. The course will cover topics such as:

Nonlinear systems of equations
Methods for solving dynamic models including topological, analytic and numeric.
Newtownian-Lagrangian dynamics
Linear dynamic systems including phase plane analysis
Chaos in forced oscillation systems
Introduction to fractal analysis and strange attractors
Stability analysis
Nonlinear Progamming functions
Perturbations, Scaling

Statistics and Probability

The course approach will be similar in style to one already in place in the Mathematical Biology program at the University of Utah, where simulation and modeling are used as tools in the context of a specific biological problem (60). The goal is not to provide students with a set of tools that they apply like following a recipe, but instead to instill context based understanding of principles so that these tools can be applied to a variety of situations and problems.

3. Evaluate and assess the progress of conceptual comprehension of students in the project based curriculum with students in a normal didactic curriculum which will precede this novel approach. Adapt both curriculums to capture the aspects which work best from both to evolve a hybrid approach for teaching mathematical concepts to bioengineering undergraduates.

To do this, we will use formative evaluation techniques which are designed to provide implementation and process feedback for program adaptation. At the end of each program year for the first three years of the project, a formative evaluation will be conducted to address whether the program is being phased in appropriately, whether presentation and comprehension of the mathematical toolbox concepts are succeeding in providing the students with skills to follow the project goal of Simplicity → Complexity → Simplicity. We will address issues such as are adequate tools available for students to use, are there issues regarding access to tools (hardware or software limitations) that are preventing full dissemination of these concepts, is the methodology of project context based presentation of the material adequate to promote comprehension, are the students succeeding in migrating skills among problems.

During the fifth year of the program, a summative evaluation will be performed for students in the project based curriculum and for students in the traditional curriculum. This evaluation will attempt to determine the aspects of each program which appear to be most successful in order to combine them in a hybrid fashion for the next three years of the program. Following these recommendations, the formative evaluation will be modified as needed and reapplied during years six through eight to again address implementation issues pertinent to the project. A summative evaluation, specific to the modeling and simulation component of the total project will be completed at the end of the funding period.

Our French collaborator, G. Chauvet (11), is now developing a virtual laboratory for physiologic "experiments" which incorporates theory from his three volume treatise (11), modeling and simulation, and multi-media visualization (55). He has already developed modules for ion transport, membrane-excitability, step-gated and voltage-gated channels, and synaptic transmission, His efforts, and those of others (56), focusing on individual biophysical or biochemical components of cells and tissues, constitute an enormous resource. The challenge is to expand such efforts to address the needs of hierarchical complex systems. Chauvet is, of course, aware of, versed in, and very interested in expanding his activities, in collaboration with ours, to consider complex properties. He has agreed to serve on our International Advisory Board and to serve as a visiting professor on a regular basis (he serves as a Research Professor in the Department of Biomedical Engineering at the University of Southern California, where he visits and works regularly).

The new NIH-NCRR Center (noted in the previous section) will conduct research and development in advanced modeling, simulation, and visualization methods for solving bioelectric field problems. Johnson, MacLeod, and co-workers will create and disseminate a computational workbench to drive the development of a bioelectric problem solving environment. It should be easy to move around within such a software environment, The programs should be robust enough to support expert-users and novices alike. With their system, researchers of bioelectric fields will

An internal evaluation will be conducted by the staff and consultants of the Center for Science Education and Outreach. Individual interviews will be part of the evaluation process (see also Section I).

Grant funds will be used to support student scholarships, provide honoraria for the teachers involved, provide salaries for the summer instructors, and provide support for staff members from the Center for Science Education and Outreach.

The program will be organized, managed, and implemented by the CSEO and College of Engineering Dean's office staff, working closely with the ERC Executive Committee. Mary McDonald, Manager of CSEO, has considerable experience in summer programs, teacher inservices, science museums, and related activities directly relevant to this program.

The General and Wider Public

Measurement and Medicine is a liberal education, general science and technology course, now in the advanced planning stages, to be offered in both on campus and distance education formats. We already have experience with such projects through the *Science Without Walls: Science in Your World* course and program (31—available on www.utah.edu/cise, click on Science Without Walls).

We do not have the resources in this ERC grant to fully develop *Measurement and Medicine*. We do propose, however, to use grant funds in Years 1-5 to complete the design and planning of *Measurement and Medicine*, and to solicit the funds required to fully develop and implement the course (~ $500,000). Such a course, offered regularly via public educational television distance learning channels (local Channel 9 in Utah) will help inform and educate the public as to bioengineering in particular and engineering in general. Tentative programs and topics are (each a one hour telecast/video):

Course 1: Measurement in Physiology - Are You Normal?

Prog 1: You are Abnormal!	Prog 6: You Can't Even Break Even	Prog 11: Newton Rules Biology & You
Prog 2: You are Imperfect?	Prog 7: Hot Stuff - Warm Blood	Prog 12: Where Did the Energy Go?
Prog 3: Lies and Electrons	Prog 8: The Body Electric	Prog 13: Senses and Sensibility
Prog 4: More Power to You	Prog 9: The Body Magnetic?	Prog 14: The Photon World
Prog 5: Hiking, Diving, and Running.	Prog 10: Gravity Wins!	Prog 15: Summary

Course 2: Measurement, Pathology, and Medicine - How Abnormal Are You?

Prog 16: You're Even more Abnormal!	Prog 21: Cystic Fibrosis and Oxygen	Prog 26: Neurodegenerative Diseases
Prog 17: Multiplying and Killing Cells	Prog 22: Hypertension and Heart Disease	Prog 27: Nerves and Brains
Prog 18: It's Your Parents' Fault!	Prog 23: Hopeless Organs	Prog 28: New Eyes and Ears
Prog 19: Problem Babies	Prog 24: Artifical Organs	Prog 29: Bio-Hybrid Devices
Prog 20: Diabetes and Metabolism	Prog 25: Old Bones - and Joints	Prog 30: Summary

Dissemination

We will work closely with our participating institutions, advisors, the BMES, IEEE-EMBS, ASEE, AIMBE, Whitaker Foundation, and other groups to inform the wider community and to encourage their participation and involvement.

I. Assessment, Evaluation, and Advisory Boards

Assessment and Evaluation

We will work with Carl Jaffe, M.D. (letter in Appendix A) and the Center for Advanced Instructional Media to structure an assessment program for this project. The Yale Center has been responsible for computer based self-test assessment programs which can be accessed via the world wide web. We will determine a set of criteria for comprehensive knowledge and design/problem solving skills which we anticipate the students will acquire during their projects and courses. Irrespective of the specific projects, there will be fundamental tools which will be presented to the students through the curriculum in each year. We will assess the student's ability to understand these principles via computerized evaluation. The evaluations will present the student with a situation that is different from their project based curriculum experience yet utilizes the same skills. The evaluations will enable us to gauge the students' ability to apply these concepts to other areas. Students will complete these evaluations at regular intervals but will only address the concepts which they understand at the time of evaluation. As they progress through the curriculum, they will participate in more extensive evaluations as their education expands.

We will use this information to compare how well these core principles are understood between project groups. This will provide comparative input between different projects to determine whether one project's method of presenting a concept may be more lucid than another project's. Since different projects will cover these concepts in different sequential order, this method of evaluation will allow comprehension to be measured at different times rather than at specified points in the curriculum. The dynamic basis of this evaluation allows for adaptation to be made in the curriculum for situations where a core principle is not well understood from a particular project or for a particular project group. This data will be stored in an interactive database that can be queried.

Yale's Center for Advanced Instructional Media (C/AIM), founded in 1987, develops innovative educational and communications programs using interactive multimedia by employing the newly emerging computing and digital network technology. C/AIM is a recognized leader in information design, medical illustration, and interface design for electronic publications and networked information systems.

C/AIM has a variety of on-going research and education projects involving multimedia software design and networked delivery of multimedia educational resources including course for first-year medical students, biomedical engineering curriculum support programs, Web-based student testing and professional post-graduate self-assessment, graphic design for the user interface, and interactive three-dimensional graphics in medical visualization. We have worked closely with Carl Jaffe on other projects and look forward to learning a great deal from him and C/AIM on these topics.

We will also work closely with our Advisory Boards (next section) to develop appropriate assessment tools, with particular attention to the needs and input of our advisors from industry.

Advisory Boards

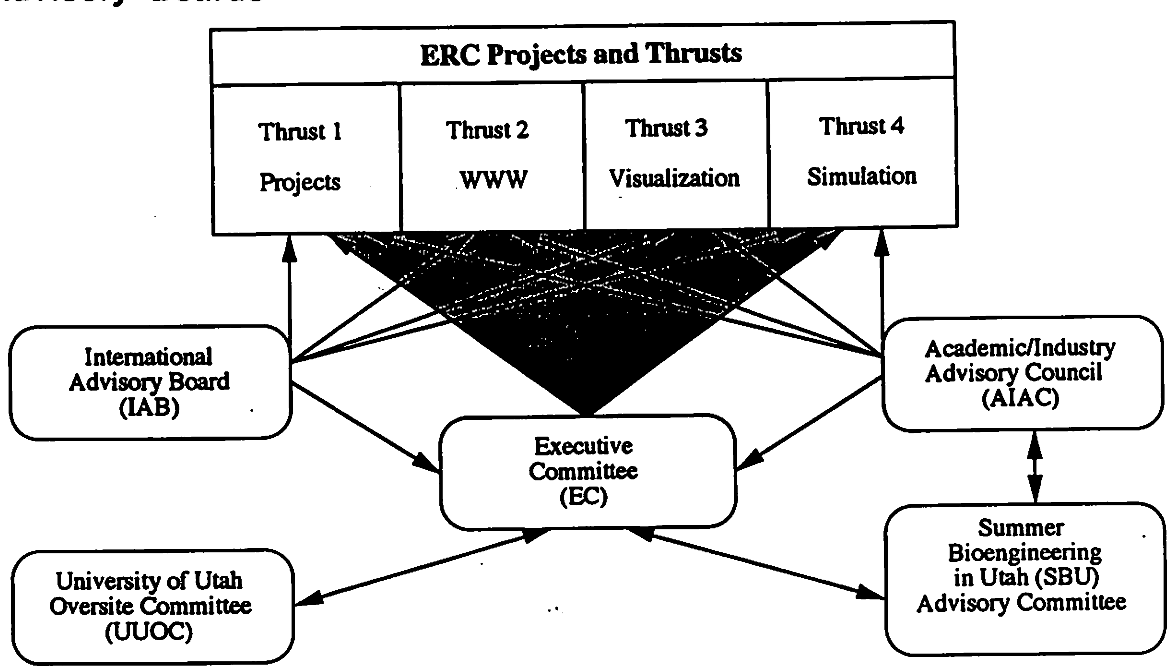


Figure 5. The several advisory boards to be organized and utilized in this ERC.

The International Advisory Board (IAB) has not yet been assembled. We have talked with some prospective members. Some of the people we expect to involve are represented in the References (4, 11, 13, 19, 32, 33, 38, 41, 42, 46, 47, 48, 53-56, 63). There are also several others we are considering. Gilbert Chauvet will be a key member and participant. We frankly expect to ask one or more of the PI's of other ERC NSF 98-68 applicants to participate, as all of these programs certainly have ideas and experience relevant to our efforts and goals. The IAB will meet annually at the University of Utah, beginning approximately in September, 1999, to provide input, critique, advice, and assessment. We are planning for about 12 members. Their expenses and honoraria are budgeted (token honoraria of $400/day, well within NSF/NIH guidelines).

The Academic/Industry Advisory Council (AIAC) is discussed in the next section.

The University of Utah Oversight Committee (UUOC) is described in Section K on Infrastructure.

The Summer Bioengineering in Utah (SBU) Advisory Committee (the high school summer program noted in Section H) will include the ERC Director (in Section K), Mary McDonald (Manager of the Center for Science Education and Outreach), Brett Moulding (State Office of Education), and the current President of the Utah Science Teachers' Association (USTA). That group will meet quarterly to plan and assess the summer programs. Their first meeting will occur in April, 1999 to rapidly plan the first program, Summer, 1999.

Only the International Advisory Board and the academic participants of the AIAB will receive honoraria.

J Industrial and Academic Collaboration

Industrial and academic collaborators were listed in the List of Participants at the very front of the application.

Participating Institutions

Initial participating institutions include the University of Southern California (Los Angeles), Drexel University (Philadelphia), University of California-Berkeley, Utah State University (Logan), Marquette University of Angers (France), Uppsala University (Sweden), and Fachhochschule Hamburg Department of Engineering (Germany). Each participating institution is represented on the Academic/Industry Advisory Council, which will provide input and guidance related to academic issues and opportunities in the ERC. These participating institutions will also be directly involved in the ERC's visiting faculty program wherein their faculty members will be in residence at the University of Utah for periods ranging from days to months, depending on schedules, needs and resources available. In addition, participating faculty in the participating institutions will be available via the Web and by telephone to serve as advisors and consultants on the student projects and on other components of the ERC (Figure 3). Depending on the specific institution and its resources and needs, we anticipate an exchange and trade of curricular materials and even courses via the world wide web. It is likely that there will be some student exchange as well.

The basic idea is to make the resources and new tools of the ERC available initially to participating institutions. We expect the number of participating institutions to grow significantly during the first several years of the ERC. Indeed, we plan to invite all institutions who submitted proposals to this ERC competition to participate.

These participating institutions will then serve as a very effective test mechanism for ERC developed curricula and tools as well as a dissemination mechanism for those deliverables produced via the ERC.

We will also work with the Council of Academic Programs of the American Institute for Medical and Biological Engineering (AIMBE) and the Biomedical Engineering Society (BMES). The participating institutions will assist the University of Utah and the ERC staff in testing and disseminating all products and activities of the program.

Participating Industries

Our Department has substantial industry interaction and involvement. The Department's Industrial advisory Board is active and involved, including developing and presenting several industrially relevant courses and seminar series. Our Center for Biopolymers at Interfaces, V. Hlady, Director, has 20 member companies. Most of our faculty consult, and many are involved with start up companies.

Given the short time line from announcement to deadline for NSF 98-68, we have not yet approached many firms as potential participants. We are confident, however, that there will be considerable industrial interest and involvement in our activities. First the integrating projects themselves are of interest to specific companies. There are several companies directly interested in the WWW as an interactive, collaborative tool. Several software firms are specifically interested in Thrusts 2-4, and many firms are interested in the future graduates of this program.

Our confirmed industrial participant list at this time is small, not because of lack of interest but simply due to lack of time.

Those we have approached and involved to date are:

Ash, O.	Executive Director, ARUP, Inc. (Associated Regional University Pathologists, Inc.) a major clinical and diagnostic testing laboratory.
*Blake, L.	Vice President, Sorenson-Vision, Inc., Logan, Utah—a data compression company whose technology allows full time video over normal telephone lines.
DiCaprio, V.	Senior Vice President & Chief Technical Officer, Becton-Dickinson Co.
*Jacobson, S.	President, Sarcos, Inc., Salt Lake City, a pioneering and leading firm in robotics and advanced biomedical products (www.sarcos.com)
*Johnson, R.	Principle of nDV Ltd., whose unique parallel coordinates software is described in Thrust 3—Visualization.
McRea, J.	Chairman, Dept. of Bioengineering Industrial Advisory Board and President/CEO, Device-Based Therapeutics, Inc., Salt Lake City
Suggett, A.	Director of R & D, Smith and Nephew Ltd., London
*Van Wagenen, R.	Vice President for R & D, Protein Solutions, Inc., Salt Lake City

* letter in Appendix A

K. ERC Infrastructure

Leadership and Management

ERC management and administration will be located in the Dept. of Bioengineering. Center Director Andrade will devote at least 25% time to the project. The ERC Executive Committee, chaired by J. Andrade, Director and co-chair of the Department, will include

K. Horch, co-Chair and co-leader of Thrusts 1, 2, and 3;
R. Rabbitt, Director of Graduate Studies and co-leader Thrust 2;
S. Kern, co-leader Thrust 3;
J. Wiskin, co-leader Thrust 4;
R. MacLeod, co-PI of new NIH NCRR and co-leader Thrust 4;
D. Christensen, Director of Undergraduate Studies and co-leader Thrust 1.

Andrade, Horch, and Kern, the three co-PIs, will be responsible for day to day implementation and management.

The Executive Committee will meet at least monthly, as will each of the research thrust groups. At each monthly meeting each of the thrust groups will present progress reports and plans for the next month. An annual presentation will be made to the joint meeting of the International Advisory Board and the Academic/Industry Advisory Council.

Department of Bioengineering:

As the project-based curriculum expands and develops, we expect that most of our undergraduate students will want to participate. Our traditional undergraduate program is designed for 35 students--this ERC is for 15 to 20. We may well choose to restructure our entire undergraduate program in Year 8 and beyond to reflect the best of both approaches, perhaps settling on a total class of 25 to 35. If this happens existing Department resources could provide much of the ongoing support. There are also economies of scale with more projects and a larger class.

Summary:

We are confident that, using the four sources noted above, we can fully support ERC activities beyond Year 8. We are committed. The key to dealing with complex socio-political systems is not unlike dealing with complex biological systems -- in E. O. Wilson's words again: "Knowledge, Obsession, Daring."

Role of ERC Within Institution

This has already been discussed. We are a collaborative place. Our academic retention, promotion, and tenure (RPT) criteria are rigorous and require strong, peer-reviewed evidence of independence, originality, significance, and quality. But that does not mean that we discourage collaboration or multi- and inter-disciplinary activity. Just the opposite. The entire Administration, from Department co-chairs to the President, encourage and support collaborative interests and activities.

Management issues were discussed in the beginning of this Section.

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Appendices

A. Letters of Interest and Involvement
B. Budget Estimates and Financial Plan (refer also to Section K)
C. Biographical Sketches
D. Facilities and Equipment (refer also to section K)
E. Current and Pending Support
F. Justification for Secretarial and Administrative Support (refer also to Budget Justification, Appendix B)