Harvard University Bioengineering

Engineering Biology for the 21st Century
A Plan for Bioengineering at Harvard

INTRODUCTION: *BROAD VISION*

Biology increasingly offers inspiration for engineering: living systems are robust to changing environments, can produce materials and structures that are far outside the current scope of nanotechnology, efficiently capture energy directly from the sun, transform pollutants into innocuous substances, and self-organize in many non-trivial ways. At the same time, ideas and tools embodied in physical and computer sciences are being brought to bear upon important challenges in biology, and engineering can provide a formal platform by which to bring rigor and quantification to physiology and medicine. There is enormous potential for the transformation of bioengineering into a discipline directed toward synthesis of technologies that can have profound impact on human well-being and the future of the planet. Bioengineering is also an exciting, deeply interdisciplinary, intellectual area that naturally integrates physical, life and information sciences. The absence of a defined Program in Bioengineering at Harvard deprives numerous students of a formal curriculum in this area, marginalizes the University in one of the major growth areas in science and health policy and limits the development of the discipline. The committee (see Appendix 1) heard of the demand to create a Bioengineering Program from students, fellows and faculty and strongly and unanimously endorsed the foundation of research and education initiatives in bioengineering.

Harvard has a unique opportunity to create a program that will define bioengineering for the 21st century. We envision the **H**arvard **U**niversity **B**ioengineering initiative to become a **hub** and a worldwide focal point of pedagogy and collaborative and translational research of life scientists and engineers working together. The University will bring together its schools of engineering, medicine, law, business and public healthcare and policy, to create a unique interschool bioengineering program. Such a program will lead to fundamental advances in biology, medicine and biomimetic engineering and could have an enormous impact on the well-being of the planet and the nation's economic competitiveness. Societal problems that may only be finally solved through bioengineering include an effective approach to bioenergy, using photosynthesis to directly capture and store energy in useable forms; purification of water and land using plants and microbes to detoxify compromised sources, new approaches to increasing the food supply and more powerful, cheaper and globally enabled healthcare. Major intellectual threads include abstracting concepts of life to use in non-living systems, and applying engineering concepts to the design of living systems, the question of what actually constitutes life, the creation of functional hybrids between living and non-living systems, and the re-conceptualization of biology as an information science (Fig. 1).

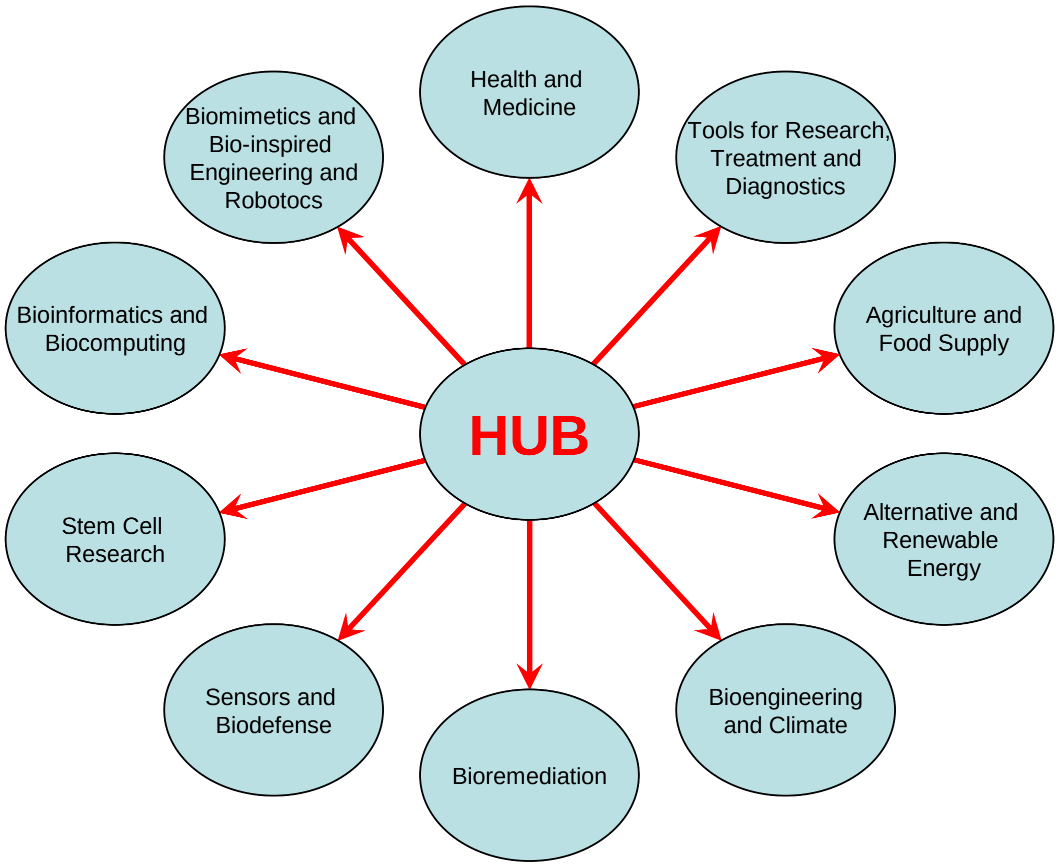


Figure 1. Bioengineering impact areas

The Harvard University Bioengineering Program would be:

1. A point of intellectual integration for engineering, medicine, molecular biology, chemistry, synthetic biology, bio-energy, systems biology, stem cell research and biological computation
2. An environment in which faculty can work as part of teams on large-scale projects that cannot be tackled by single labs
3. A place where students are challenged with new opportunities and interdisciplinary training, rather than being tunneled into a narrow specialty
4. A venue for the development of new technologies and the expanded use of emerging technologies in science
5. A nidus around which technology can be made available to a broad community of scholars and scientists
6. A starting point for commercial ventures and industrial connections
7. A place where Harvard's unique breadth and depth of expertise in medicine, biology, engineering, the physical sciences, public policy, law, economics and business would find full expression in an integrated multidisciplinary approach to a broad and centrally important topic.

WHY NOW? *THE NEED*

The global and societal need.

The major challenges surrounding human health and the welfare of the planet will be the focus of much of this century. The future presents unprecedented opportunities in the area of bioengineering, which could lead to enormous advances of potential societal and economic value. Research in biomolecular materials and processes has already yielded rich economic dividends. For example, annual U.S. sales of drug-delivery vehicles alone are projected to reach $48 billion in 2007. Advances in the science and engineering associated with biomolecular processes and medicine will aid the nation's progress in many areas including healthcare cost reduction, preventive/anticipatory medicine, energy independence, delivery of improved medical therapeutics, and the creation of reliable sensors to detect biological and chemical threats. *The nation's economic competitiveness and well-being demand vigorous pursuit of research and education in bioengineering.*

The discipline and scientific need.

Life sciences have reached a turning point. A large number of basic mechanisms have been discovered, and the essential mystery of life has been stripped away by the last 50 years of molecular biology. But this tremendous progress has now led us to an understanding of just how complex biology really is. Biology now needs large infusions of conceptual and quantitative approaches from information science and the physical sciences. Biology needs to be converted into a rigorous, predictive science through computation, theory, and model building, and into a field that is truly useful to society, through engineering. Chemistry went through a similar transition – at a certain point, the basic mechanisms of chemistry were explained in terms of quantum mechanics. To stay vibrant, chemistry became more applied and interfaced with other disciplines such as materials science and biochemistry. Biology is only now ready for deep engagement with engineering.

Engineering and physical sciences are, in turn, longing for new challenges. The first generation of biomedical engineering has yielded revolutionary advances, including new imaging modalities, prosthetic devices, dialysis, and drug delivery systems, and this field is poised to tackle increasingly complex and sophisticated problems. Physical sciences have been remarkably successful in developing approaches to understand and control the physical world. However, despite substantial effort, these approaches have often not led to a rational framework for important biological problems. There is much basic science to develop to fully harness the potential of biology. In engineering, powerful new methods of nanoscale fabrication, characterization, and simulation – using tools that were not available as little as five years ago – are creating new opportunities for understanding, manipulating and mimicking biological materials and processes; computer science is finding new ways to mimic and model biological processes, and increasingly is giving biologists new ways to think about biology. Multidisciplinary research at the interface between engineering, life and physical sciences is the fastest growing area in the modern science presenting unique opportunities for scientific discovery and development (see Fig. 2).

Successfully addressing these opportunities and challenges represents one of the great frontiers of the rapidly evolving field of bioengineering (see Fig. 3). The very strengths and attractions of bioengineering present significant limitations and trials to those who seek to take it forward. Like many emerging fields bioengineering has meant different things to different people. Similarly, the many disciplines bioengineering embraces (see table) challenge the pursuit of excellence in all domains. These restrictions have at times prevented rational development and growth of bioengineering to its full potential. The Committee strongly believes that *bioengineering is the natural next step in the intellectual development of biology, medicine and engineering; as an evolving discipline, it requires careful definition and leadership.*

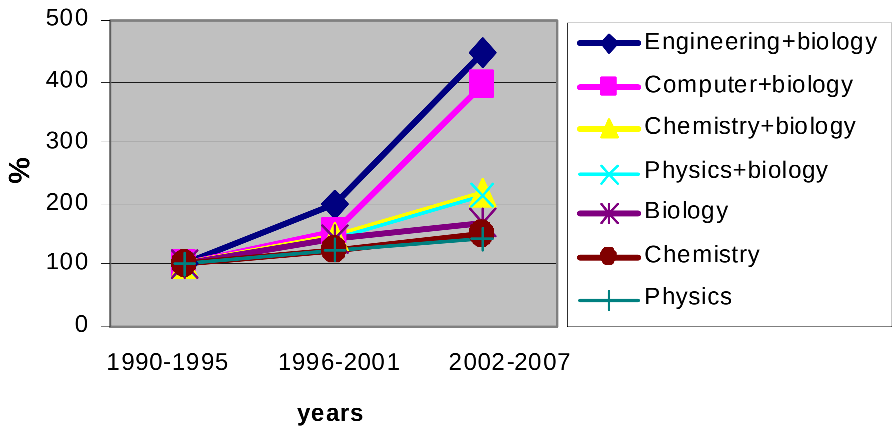


Figure 2. Chart showing the number of papers published in collaboration between departments of biology/medical schools and physical sciences/engineering as compared to the number of papers published by single departments (ISI Science Database Search)

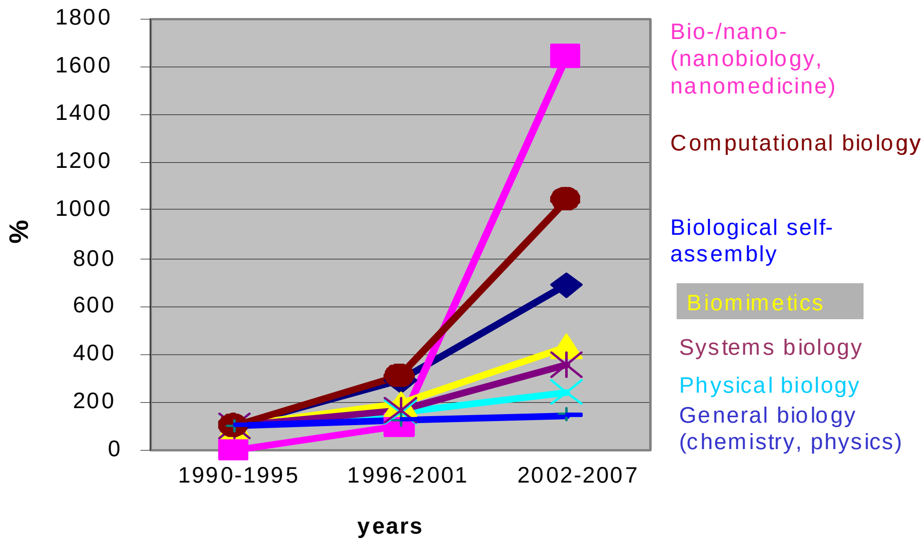


Figure 3. Chart showing the increase in the number of papers published in the emerging areas of interdisciplinary life, engineering and physical sciences compared to the number of papers in individual disciplines (ISI Science Database Search)

Table. Examples of Intellectual Sub-Disciplines of Bioengineering

Broad Intellectual Area	Examples[1]	Sample outcomes
Engineering of new tools for medicine and biology	- new modes for non-invasive diagnosis - new non-invasive therapies - novel materials, e.g. for drug delivery - technology for nurses/paramedics/first responders - bioMEMS - image analysis (whole body/cells)	- improved, cheaper healthcare - more powerful research tools - continuous lifetime monitoring - in vivo imaging at all scales - autonomous, dynamic therapies that monitor and respond to disease in real time - telemedicine
Engineering using genetics, molecular biology and systems biology	- bio-nanotechnology - bioenergy - bioremediation - phage display and panning - live animal sensors - engineered viruses and bacteria for sensing and therapeutics	- cells that build computational chips - biological batteries - viruses that target specific cancers - genetics-enabled, patient-specific medicine - biological factories for synthesis and assembly
Engineering using cell and developmental biology, organismal biology	- tissue engineering and regeneration - chimeric and transgenic animals - biomechanics - engineering the immune system - 3D in vitro tissue models	- broadly compatible eye, pancreatic islets, heart, kidney, etc. - replacements for worn-out or damaged organs - new vaccines for cancer and infectious diseases - treatments for autoimmune diseases - improved drug screening
Biological inspiration for engineering and technology	- robotics and automation - bio-inspired materials and design - biomimetics - miniaturization and nanotechnology - self-assembling structures and devices - responsive materials - complexity and emergent behavior	- robots that self-organize to automatically repair - materials that adapt to circumstances - materials and devices that evolve - multifunctional materials - energy harvesting and storage devices - environmentally friendly chemical processing
Quantitative biology	- computational biology - bio- and medical informatics - bio-inspired agent-based or rule-based computing approaches - non-linear, dynamic phenomena	- computers with immune systems - bio-inspired robustness and adaptation in computer operating systems - neural networks - rationally-designed targets for disease intervention - virtual models of cells, organs, and humans

[1] The more detailed list of areas considered by the Committee is presented in Appendix 2.

Harvard University need.

Harvard's intellectual and educational leadership in modern science is largely impossible without a substantial effort in bioengineering. Given that this is Harvard, there is a communal and global ***responsibility*** to continue the development of the bioengineering discipline not only within the university but also outside, and to use it to benefit society. Fully addressing these goals will involve academia, industry (nascent and existing), healthcare policy, regulation, law and global health.

The synergistic development and application of approaches that have traditionally been confined to either engineering, life, physical or medical sciences within the boundaries of SEAS, FAS or HMS are already emerging organically at Harvard. A range of Harvard University assets have contributed greatly to biomedical sciences. Molecular biology began in large part at Harvard. The Harvard School of Public Health has made major contributions to international health and public policy. Imaging sciences thrive in Harvard-affiliated hospitals. The Department of Systems Biology at the Medical School and the Bauer Center at the FAS are setting new standards for computational and quantitative biology. Faculty associated with Health Sciences and Technology (HST) have contributed to advances in biomedical engineering and teaching to date. The Broad Institute is a new paradigm in research organization and financing. Chemical biology, neuroscience, biophysics and systems biology have all developed cross-School efforts. The Department of Stem Cells and Regenerative Medicine is the first Department to be explicitly shared between two Schools. Yet, there has not been an overarching program at a University-wide level to provide core strength in bioengineering. The advances are at the rudimentary stage and there is much to be done to ensure that the beneficial progress in removing institutional barriers continues. These and other like programs can be leveraged to build even greater internal strength in the bioengineering domain. Moreover, each of these University initiatives and resources would be strengthened greatly by a sound and secure program in bioengineering.

In this sense, investing in bioengineering is an enormous opportunity to contribute to the field in general, fill internal voids and strengthen existing programs. But the changing nature of this field leads to the situation that no single Harvard program or school, be it HSEAS, HMS or others, can mount a convincing effort in bioengineering alone. Together—by consolidating the faculty and resources and by harnessing Harvard's strengths (HMS & hospitals, HSEAS, FAS, HSPH, HBS, and HLS)—we can conceive a new approach and definition of this discipline and create a program that will lead the world in this important area. *This is an opportunity for Harvard to create a new structure that MUST cross School boundaries, and that will generate enormous excitement for collaboration among the Schools to address major overarching problems in human health and bio-inspired technologies.*

Educational need.

Bioengineering is becoming extremely popular with students from many different backgrounds. The potential of bioengineering to bring together disparate subjects of biology and engineering and, literally, to change the world will most definitely engage the excitement and passion of Harvard undergraduates. We have already had considerable experience of this with the success of programs like iGEM and the medically-focused HST program. The number of undergraduate and graduate students interested in bioengineering is growing exponentially. This tendency creates a substantial, and largely unsatisfied, demand for a specialized program in bioengineering. The student population interested in bioengineering is highly diverse, as is the discipline itself. Yet, it should be recognized that the Harvard student is unique, not by virtue of drive, accomplishment or intelligence but by perspective and insight. It is critical to develop a new, robust but rigorous program and qualification criteria that revolutionize multidisciplinary teaching and respond to the specific and distinctive needs of Harvard students. There must be sufficient faculty and resources to meet all advisory, supervisory and mentoring needs of the student body. *To address this growing student-driven need, the university has a responsibility to create a structure to support the educational diversity associated with the bioengineering* *discipline and to facilitate curriculum development to train the next generation of Harvard students.*

OVERALL OBJECTIVES

A key issue in establishing a bioengineering program at Harvard is to decide what the program is to accomplish. The field is, in principle, so broad that without a focused set of goals it could fail to develop as a coherent intellectual effort. This has been a particularly difficult issue for the Committee, and the focus of much discussion. There are many extremely attractive areas within bioengineering, and each member of the Committee might choose a different set of possibilities as the most exciting areas to focus on. In the end, the Committee concluded that the choice of focus areas should not be the primary issue at this stage. What is important is to define a scale of operations and a process for identifying a leader. In thinking about the scale of operations that is required, it is worth considering what a bioengineering effort will need to achieve:

1. Make Harvard a leader in bioengineering, by creating a truly cohesive, interdisciplinary program that bridges HSEAS, HMS and the Harvard-affiliated hospitals
2. Develop a new academic discipline and curricula at both the graduate and undergraduate level that would be a model for other Universities
3. Solve important, fundamental scientific problems related to the basic principles of biological design and function through the integration of technical innovation within society
4. Apply this knowledge to
    a. Innovative medicine through engineering
    b. Innovative engineering through biological inspiration
    c. Global-scale problems in energy, water, environment, and sustainability
    d. Research tools to accelerate the development of new understanding of biological phenomena
5. Generate a new type of student able to integrate knowledge in life, physical, and information sciences, and to apply the resulting understanding to the solution of global problems, and to the solution of grand-scale intellectual challenges
6. Create jobs and companies

Creating a leading program in bioengineering and forging the next generation of this evolving academic discipline are both goals that indicate the need for major new resources, and strong leadership. The committee recommends that *Harvard should launch an international search for a senior figure in bioengineering immediately*, and shape the resources, goals, and organizational structure for bioengineering around the leader who is identified as a result of the search. We should recognize that the resources required will be on a scale at least commensurate with starting a new Department—although many organizational models are possible (see below).

RECOMMENDATIONS

General recommendations.

Recommendation #1. ***Create a new inter-school program – Harvard University Bioengineering (HUB).*** Harvard has all the assets to make the HUB special: HMS & hospitals house the world's most renowned Medical School and biomedical research; the HSEAS's unique mission of "Engineering a Renaissance" laid the foundation for a highly innovative, interdisciplinary engineering program rooted in the basic and applied sciences. However, the Committee reiterated that neither SEAS nor HMS could mount a convincing effort in bioengineering alone. By creating a new joint effort, we will be able to harness Harvard's strengths (primarily at HSEAS and HMS & hospitals, but also at FAS, HSPH, HBS, HLS, and interschool programs like the Stem Cell, Broad Institutes and HST) in contributing to the rationale, evolution and growth of the Bioengineering discipline. We will create a truly unique Harvard program that will thrive on applied sciences, will integrate innovative medicine through engineering with advanced engineering through biological inspiration and will lead the world in this important area (Fig. 4).

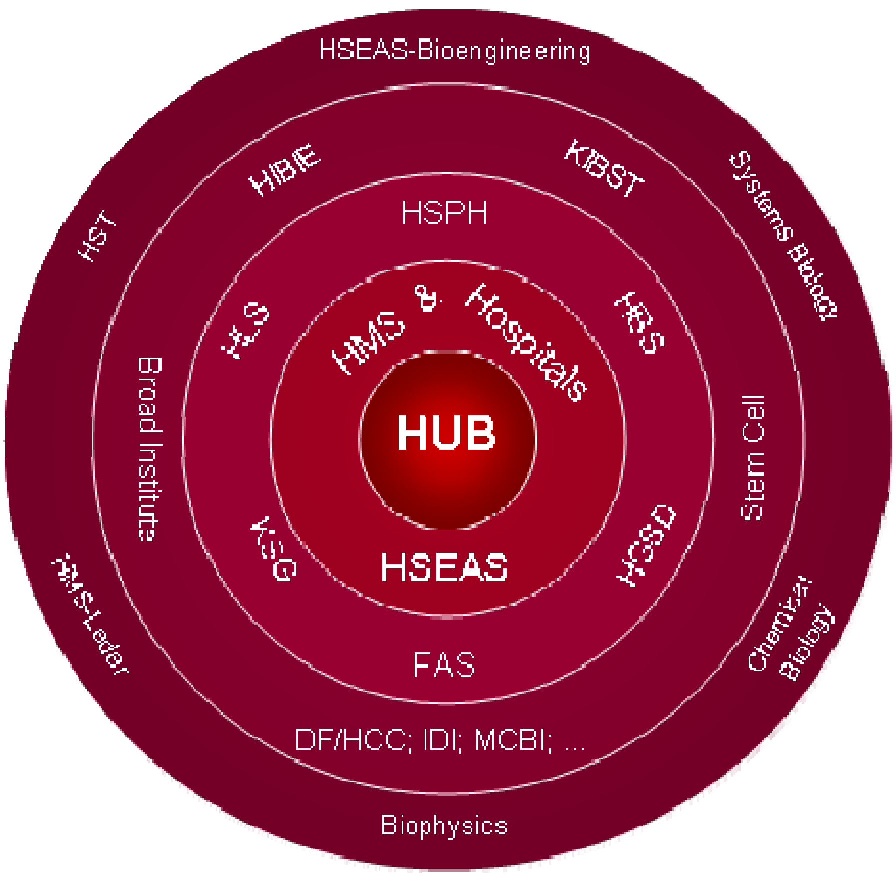


Figure 4. Inter-school Harvard University Bioengineering program (HUB). 1st shell – core Schools; 2nd shell – other participating Schools; 3rd shell – Institutes and Centers; 4th shell – educational components

Recommendation #2. ***Launch an international search for a leader for HUB.*** We recommend the HUB be led by a Director, who will be hired as a result of an international search. The Committee felt that this search should be given a high priority, as the new program of such caliber, importance and complexity cannot succeed without dedicated governance. We recommend that this search be initiated immediately, and led by the Deans of HSEAS and HMS.

Recommendation #3. ***Create an Inter-School Committee to build the Bioengineering community.*** The Committee recommends that to maintain the momentum of these discussions, an Inter-School Committee (ISC[*]) on Bioengineering, reporting to the deans of SEAS and HMS, should be immediately created and given resources and space. The Bioengineering ISC would build on the efforts that have already started among existing Bioengineering faculty and create new educational and research opportunities across HU's schools of engineering, medicine, law, business and public healthcare and policy. It should have resources including committed space to establish needed cores and to catalyze the formation of interdisciplinary and inter-faculty projects. The ISC will also engage and integrate into its structure the existing inter-faculty efforts (HIBIE and Kavli) in this area. The Committee specially emphasized the synergistic relationships between HIBIE and the Bioengineering ISC and recognized the importance of integrating HIBIE into the broader bioengineering effort (HUB).

Recommendation #4. ***Set aside a minimum of 20 new faculty hires to build and grow the Bioengineering effort***. We envisage that these new hires should be made only after the Director has been selected and an intellectual focus has been approved by the HSEAS and HMS Deans and University leadership. The Committee strongly recommends many of these hires involve cross-school appointments, in order to enhance the bridge-building between the different participating units. Negotiations to transfer existing faculty to the new effort should also commence after the vision is clear. The focus should be on strengthening Harvard's effort by making these new recruitments possible, rather than on rearranging existing faculty; however, if senior leadership is available in a given intellectual area, some rearrangements may be important to catalyze rapid progress. It is noted that the organizational structure of HSEAS does not involve Departments, whereas the structure of HMS is built upon them. As the bioengineering effort grows significantly in size, prominence and impact, a working group should be set up to explore the structures of existing cross-Faculty initiatives (e.g. SCRB, MSI) and evaluate how these models would support the goals of HUB. These findings should be discussed with the Director, once identified, and a consideration should be given to the ISC transitioning into a new Division or Inter-School Department with a subsequent further increase in faculty hires.

Recommendation #5. ***Create a central location that houses a critical mass of the Bioengineering research and administrative functions.*** The Committee felt that Bioengineering cannot be successful if it is distributed across campus with no central home or identity. The central location is expected to be at the new Science 1 complex at the Allston campus.

[*] The ISC will be created according to the recommendations of the University Planning Committee for Science and Engineering (UPCSE) and Harvard University Science and Engineering Committee (HUSEC).

Educational recommendations.

Being at the interface between traditional engineering and life sciences, bioengineering education faces an enormous challenge of combining the engineering and biological curricula in a meaningful way and producing a robust program that develops a mindset of a bioengineer – an engineer capable of tackling the society's pressing problems related to healthcare, preventive/anticipatory medicine, energy independence, or the creation of reliable sensors to detect biological and chemical threats. The committee discussed educational issues and alternatives that focus on teaching research concepts and research methods in bioengineering. Two approaches were compared: (a) providing courses in the specific aspects of bioengineering or (b) a formal degree-granting curriculum. The consensus was to support the latter at both the undergraduate and graduate levels. The committee felt that these new activities should be designed and implemented to further strengthen the important connection to clinical medicine through HMS & hospitals, and to deepen the medical and non-medical aspects of the biologically-inspired engineering program. The committee agreed that this is a place where Harvard could have enormous impact. By starting anew, rather than simply cobbling existing courses together, Harvard could create a cohesive bioengineering program. There was considerable enthusiasm for this within the committee, and we believe the bioengineering community will embrace this new teaching mission with gusto.

Recommendation #6: ***Create a new undergraduate concentration in bioengineering.*** This concentration should prepare students for the practice of bioengineering, and also provide adequate preparation for graduate study in engineering, the sciences, and other professions. A focused curriculum, with emphasis on mathematics that integrates a solid understanding of engineering principles with quantitative thinking relevant to fundamental concepts in biology, will be required to train engineers who can apply science and technology to society's pressing problems. The engineering techniques and biological problems should be taught together as much as possible. Due to the current undergraduate teaching infrastructure in SEAS, and its integration within FAS, it was felt that SEAS should take the lead role in the creation of an undergraduate concentration. We anticipate that the core courses will be offered through the HSEAS, but a variety of courses will be available through other departments in FAS and HMS and the curriculum will be planned by a cross-faculty curriculum committee to reflect the interdisciplinary nature of Bioengineering. Educational events involving law and policy faculty will be included in the curriculum to motivate thoughtful discussions of social and ethical issues related to scientific advances in bioengineering. In order to broaden and enrich the training, the students will have an early immersion in research. It is critical to provide additional teaching laboratory space, and new instructional and lab support staff and adequate resources.

Due to the breadth of the bioengineering field and the associated difficulty in preparing students adequately in its fundamentals, we further recommend that consideration be given to initially offering only a S.B. degree in this new concentration.

Recommendation #7: ***Develop a graduate curriculum in bioengineering.*** The committee favored the creation of a new cross-school graduate program administered jointly by HMS and SEAS, although some committee members thought students could also be served by expanding and adapting existing cross-School graduate programs instead; both options may be possible.

Natural interfaces exist between the new program and the existing HST, Biophysics and Systems Biology graduate programs, and the bioengineering program should coordinate its activities with these programs to provide synergy, and avoid detracting from the mission and success of those programs. Indeed, the new bioengineering program should be structured and implemented in a manner that enhances the educational mission of HST and exploits this existing interface between bioengineering and clinical medicine. In either case, we would aim to prepare students for a career in research and/or teaching in academics or industry. A new graduate program should be joint between HMS and SEAS, with both teaching responsibilities and research opportunities distributed among the Harvard schools, hospitals and clinics. The program must provide a balance of formal and laboratory-based engineering, biological, and medical training to adequately prepare students both to be successful at this interface and to enable these students to define the bioengineering field in the future. The graduate program should engage students early in research, broaden exposure to the discipline through cross-school interactions, foster leadership and mentoring skills, offer opportunities for outside internships, and — most of all — provide an intellectually stimulating interdisciplinary research experience.

Next steps for education

It was understood that these recommendations will require significant further programmatic definition. *To address these challenges, the Committee recommends an immediate creation of the Bioengineering Undergraduate and Graduate Planning Groups that will be charged to define Bioengineering as a discipline at the undergraduate and graduate levels, to identify specific coherent and consistent educational models and develop the curriculum for the degree.* Issues to be resolved include University approval of the number of students to be admitted, how such students will be selected, the admissions processes, and curriculum definition, delineation, evaluation and oversight. In addition, it is anticipated that the University will insist on a description of the formal series of checks and balances and quality control for all aspects of the undergraduate and graduate programs, including student mentoring, qualification examination, and means to evaluate adherence to specific and general degree requirements. The committee encourages involvement of the Directors of the graduate program in Systems Biology, Biophysics, the medical and graduate programs of HST, and the Howard Hughes Medical Institute (HHMI) programs in Translational Research (the HMS Leder and HST GEMS) in these discussions.

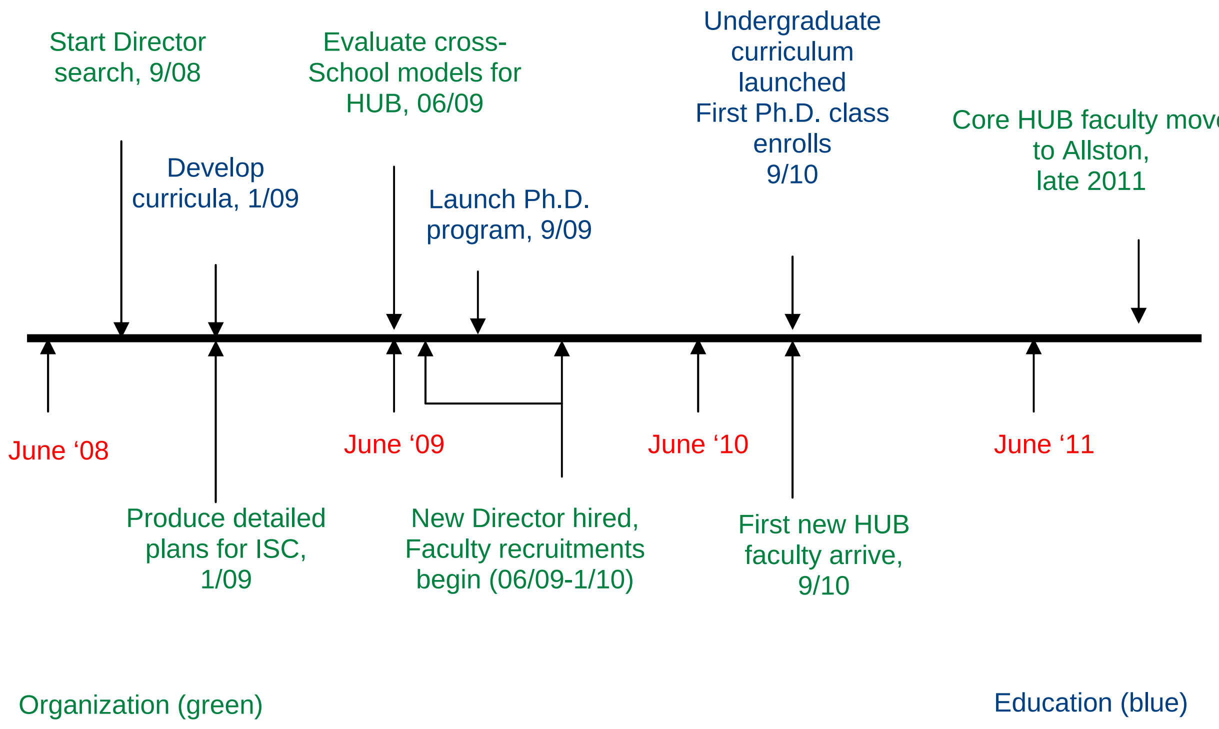
The working groups should identify avenues to promote and sustain Harvard's leading position in providing the world's best preparation in research. The specific recommendations should address legislation, policy, research and practice and provide resources for enacting prioritized choices for Deans, Faculty and Administrators. Critical opportunities for growth should be identified as bioengineering emerges as a new discipline at Harvard with significant prominence and impact.

Finally there was desire to coordinate all these educational initiatives so that they could not only present a uniform face to the outside world (e.g. web-based information dissemination to potential students) but also facilitate cataloguing and support of resources for education in the field. Such an effort will serve current and potential students but also faculty, recruits and leadership.

The Committee believes that dramatic developments in engineering education and research and lessons learned from bioengineering programs in other universities provide significant leverage for addressing the major educational challenges we see in this area. The Committee emphasized, however, that success will only be possible with University-wide support, sustained effort, and funding.

TIMELINE

- Set up a search committee and initiate an international search for a Director of HUB (by 09/08)
- Appoint a group to develop an undergraduate and graduate bioengineering curriculum (completion by 01/09)
- Appoint a group to continue planning, or continue the existing group, to work with the relevant deans to produce a detailed plan for the ISC (01/09)
- Reach an initial agreement among the relevant deans concerning objectives, structure, budget, staffing, space, and organization of the ISC (01/09)
- Create a group (including senior administrators as well as faculty) to evaluate existing cross-School models (completion by 06/09)
- Recruit first bioengineering graduate students (09/09)
- Offer a curriculum to undergraduates (09/10).



Appendix 1: Harvard University Bioengineering Planning Group

Joanna Aizenberg, Gordon McKay Professor of Materials Science; Professor of Chemistry and Chemical Biology and Radcliffe Professor at Harvard University

Pamela Silver, Professor, Department of Systems Biology, Harvard Medical School

Dr. Elazer Edelman, Thomas D. and Virginia W. Cabot Professor of Health Sciences and Technology at MIT and Professor of Medicine at Harvard Medical School

George M. Whitesides, Woodford L. and Ann A. Flowers

David Mooney, Gordon McKay Professor of Bioengineering in the Harvard School of Engineering and Applied Sciences at Harvard University

Ralph Weissleder, MD, PhD, Professor, Harvard Medical School; Director, Center for Molecular Imaging Research

Appendix 2: Areas considered by the committee as possible foci

Engineering Solves Problems:

1. Biomedical engineering
    a. Healthcare cost reduction/Globalization
    b. Preventive/anticipatory medicine
    c. Personalized/patient-specific medicine
    d. Non- and minimally invasive medicine
    e. Sensing and quantitation
    f. Emerging disease
    g. "Urban Illness" (Drug/Alcohol/STD)
    h. Healthy aging
    i. Cognitive disease
2. Non-medical bioengineering
    a. Bioenergy
    b. Bio-inspired materials and robotics
    c. Biosphere modeling
    d. Bio and climate change
    e. Water and biology
    f. Bioremediation
    g. Agriculture
    h. Defense

More specific potential focus areas

1. Miniaturization/Nanotechnology
2. Biomaterials
3. Tools for research and treatment
4. Diagnostics
    a. imaging at all scales
    b. sensors
    c. advanced diagnostics
    d. molecular imaging in vivo (overcoming current limitations in depth of field; kinetics)
5. Robotics/Automation
6. Biologically-inspired design
7. Materials for minimally invasive therapies
8. New modes for non-invasive therapy (electrical, magnetic)
9. Engineering the immune system (infectious disease, cancer, autoimmune disease, transplantation)
10. Synthetic biology (building blocks and rules governing their assembly)
11. Programming cells in vivo
12. Autonomous, dynamic therapies (monitor and respond to disease in real time)
13. IT (from Google/Facebook to patient records to telemedicine)

14. Technology for nurses/paramedics/first-responders
15. How to integrate genetics: Patient-specific medicine
16. Continuous lifetime monitoring (d[biomarkers]/dt)
17. Cell/molecular engineering (cell mechanics)
18. Biocomputation (control theory, modeling, networks), computational biology and bioinformatics
19. Drugs (delivery, drug market, overcome existing problems)
20. Tissue engineering
21. BioMEMS (microfluidics, sensors, detectors, implantables)
22. Toxicology
23. Bio-energy and metabolic engineering

Appendix 3: Charge

The School of Engineering and Applied Sciences, the Harvard Medical School and the Faculty of Arts & Sciences are in the process of developing a joint program to enable education and research in the broadly defined area of interdisciplinary bioengineering.

We are looking for a strategic plan regarding the establishment of this program. We would like you to examine the educational and research opportunities in bioengineering across Harvard University.

- We envision that the program would reflect both breadth and novel approaches. It must also highlight opportunities for applied as well as fundamental work.
- Educational opportunities ranging from undergraduate to Ph.D. programs, and their potential relation to existing programs (e.g., HST, Systems Biology) should be investigated.
- The committee should analyze the existing and potential research scope of bioengineering activities, as well as mechanisms to more efficiently enable these activities. As the inspiration for much of bioengineering comes from the clinic, and the resulting technologies are often applied in medicine, the committee should specifically determine how bioengineering activities and structures could involve Harvard teaching hospitals, and the many engineers already on faculty at these institutions.
- The committee should aim to develop a strategy that will place Harvard at the forefront of bioengineering, paying particular attention to emerging new technologies and their application to bioengineering.

The committee should consult and discuss its findings with an advisory group (to be selected) as well as other faculty members of SEAS, HMS and FAS.

We would like to receive a draft of your report by the end of March 2008 and a final report by May 31, 2008.

We look forward to your report and we thank you for your efforts.

Joanna Aizenberg

Joanna Aizenberg, Gordon McKay Professor of Materials Science; Professor of Chemistry and Chemical Biology and Radcliffe Professor at Harvard University, pursues a broad range of research interests that include biomineralization, biomimetics, self-assembly, crystal engineering, surface chemistry, nanofabrication, biomaterials, biomechanics and biooptics. She received the B.S. degree in Chemistry in 1981, the M.S. degree in Physical Chemistry in 1984 from Moscow State University, and the Ph.D. degree in Structural Biology from the Weizmann Institute of Science in 1996.

Prior to her appointment at Harvard, Aizenberg was at Bell Labs/Lucent Technologies as a member of the Technical Staff. She made several pioneering contributions, including the development of new biomimetic approaches for the synthesis of ordered mineral films with highly controlled shapes and orientations; and the discovery of unique optical systems formed by organisms (microlenses and optical fibers) that outshine their technological analogs.

Aizenberg's selected awards include: Award of the Max-Planck Society in Biology and Materials Science, Germany, 1995; Arthur K. Doolittle Award of the American Chemical Society (ACS), 1999; New Investigator Award in Chemistry and Biology of Mineralized Tissues, 2001; ACS PROGRESS Lectureship Award, University of Wisconsin at Madison, 2004; Lucent Chairman's Award, 2005; Industrial Innovation Award, ACS 2007; Ronald Breslow Award for the Achievement in Biomimetic Chemistry, ACS 2008.

Aizenberg is a AAAS Fellow; she has been elected to the Board of Directors of the Materials Research Society (MRS) and to the Board on Physics and Astronomy of the National Academies. She is serving on the Advisory Board of *Langmuir* and *Chemistry of Materials* and on the Board of Reviewing Editors of *Science Magazine*.

Pamela Silver

Pamela Silver – Professor, Department of Systems Biology, Harvard Medical School. – Professor, Department of Systems Biology, Harvard Medical School.

Pamela Silver received her BS in Chemistry and PhD in Biochemistry from the University of California where she was an NIH Pre-doctoral Fellow. She was a Postdoctoral Fellow at Harvard University in the Dept of Biochemistry and Molecular Biology where she was a Fellow of the American Cancer Society and The Medical Foundation. Subsequently, she was an Assistant Professor in the Dept of Molecular Biology at Princeton University where she was an Established Investigator of the American Heart Association, a Research Scholar of the March of Dimes and was awarded an NSF Presidential Young Investigator Award. She moved to the Dana Farber Cancer Institute where she was a Professor in the Dept of Biological Chemistry and Molecular Pharmacology at Harvard Medical School. She was named a Claudia Adams Barr Investigator and awarded the Mentoring Award for the PhD Program in Biological and Biomedical Sciences at Harvard Medical School. In 2004, she became one of the founding members of the Department of Systems Biology at Harvard Medical School and the first Director of the Harvard University PhD Program in Systems Biology.

Her research interests range from the mechanisms of RNA movement and genome organization to the use of genomics, chemical genetics and cell-based screens in the study of diseases and drug action. She has developed an interest in the emerging field of Synthetic Biology where she is building cell-based machines and developing protein-based logic for design of novel therapeutics and engineering cells as sources of bio-energy. Some of her recent work includes the design and implementation of a cell-based memory device and the elucidation of the 'ribosome code.' Her work was recognized by an Innovation Award at BIO2007 and has been funded by grants from the NIH, DOD, NSF, Novartis, Merck and The Keck Foundation. She currently holds an NIH MERIT award.

She has served on numerous government and private advisory panels including the NIH Pioneer and Innovator Award Committees, the NAS/NRC Study on Network Science, the OSD/NA Biodefense Workshop, the Jane Coffin Childs Memorial Fund, the Novartis Oncology Program, the Swiss National Science Foundation and the Paul Glenn Institute for Aging Research. She has served on numerous editorial boards including Nature Molecular Systems Biology, BMC Systems Biology, Genes and Development, Synthetic Biology and PLoS One. She was the Editor of Molecular Biology of the Cell and has served on the Council of the American Society for Cell Biology and on the Committee for Women in Cell Biology. In addition, she has been a Visiting Professor at the University of Sao Paulo where she participated in optimization of bio-ethanol production. She also initiated and co-directs the Harvard undergraduate team for the International Genetically Engineered Machines Competition (iGEM). Recent Plenary Lectures include the NIH Director's Lecture, International Conference on Systems Biology, Karolinska Institute Frontiers in New Biology, Imperial College Symposium on Systems and Synthetic Biology, International Symposium on Systems Biology, Beijing and New Landscapes for Life Sciences: Biology and Engineering, Laussanne.

Elazer Edelman

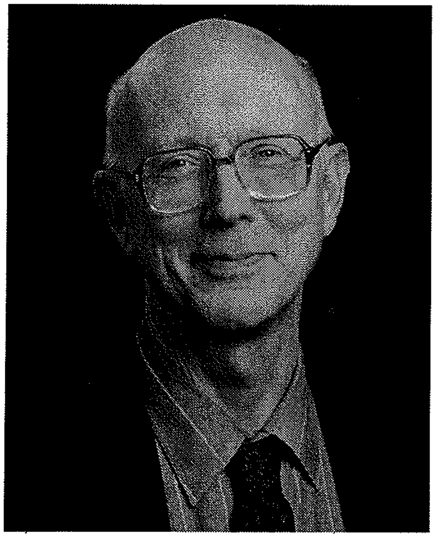
Dr. Elazer Edelman, the Thomas D. and Virginia W. Cabot Professor of Health Sciences and Technology at MIT and Professor of Medicine at Harvard Medical School, is a cardiologist at the Brigham and Women's Hospital in Boston and a pioneer in both vascular biology and the development and assessment of biotechnology. Dr. Edelman directs the Harvard-MIT Biomedical Engineering Center (BMEC), dedicated to applying the rigors of the physical sciences to elucidate fundamental biologic processes and mechanisms of disease. BMEC programs span a wide range of disciplines, with its resources made available to investigators from MIT and Harvard.

Dr. Edelman received Bachelor of Science degrees in Bioelectrical Engineering and in Applied Biology from MIT in 1978, a Masters of Science degree in Electrical Engineering and Computer Sciences from MIT in 1979, a degree in medicine from Harvard Medical School in 1983. He received his Ph.D. in Medical Engineering and Medical Physics from MIT in 1984 examining the mathematical basis of controlled drug delivery with Prof. Robert Langer. After internal medicine training and clinical fellowship in Cardiovascular Medicine at the BWH he spent six years as a research fellow in the Department of Pathology at Harvard Medical School under Prof. Morris J. Karnovsky.

His career is marked by high impact multi-disciplinary innovation, fundamental discoveries and implementation. His research focuses on understanding how tissue architecture and biochemical regulation contribute to local growth control. He was among the first to validate the hypothesis that proliferative vascular diseases are the sum of effects from endogenous growth promoters and suppressors. The applied aspects of his work flow from the umbrella of growth modulation. He reasoned that the optimal way to control a biologic event was by recapitulating natural means of regulation. Hence, polymeric controlled drug delivery systems should mimic natural release systems, and vascular implants should be devised with an intimate knowledge of the injury they induce. The development and mathematical characterization of perivascular and stent-based drug delivery is an example of the former, and design of an endovascular stent from first principles is an example of the latter.

Dr. Edelman is a fellow of the, American College of Cardiology, American Heart Association, American Institute for Medical and Biological Engineering, American Society for Clinical Investigation, and Institute of Medicine of the National Academies of Science. As an avid ice hockey goalie Dr. Edelman's most recent accomplishment involves passing three levels of coaching licensure from the Massachusetts Youth Hockey league and coaching the Brookline Bantam B team. He lives in Brookline MA with his wife Cheryl and their three sons Alex, A.J. and Austin.

George M. Whitesides



George M. Whitesides. Woodford L. and Ann A. Flowers University Professor. Born, 1939, Louisville, KY. A.B., Harvard, 1960. Ph.D., 1964, California Institute of Technology (with J.D. Roberts). Faculty: Massachusetts Institute of Technology, 1963 to 1982; Harvard University, 1982-present. **Awards:** American Chemical Society (ACS) Award in Pure Chemistry (1975). James Flack Norris Award (ACS, New England Section) (1994). Arthur C. Cope Award (ACS) (1995). Defense Advanced Research Projects Agency Award for Significant Technical Achievement (1996). National Medal of Science (1998). Von Hippel Award (Materials Research Society) (2000). Pittsburgh Analytical Chemistry Award (Society for Analytical Chemists of Pittsburgh) (2003). Kyoto Prize (2003). Paracelsus Prize (Swiss Chemical Society) (2004). Ralph and Helen Oesper Award (Cincinnati Section of ACS) (2004). Jacob Heskel Gabbay Award in Biotechnology and Medicine (2004). 2004 Dickson Prize in Science (Carnegie Mellon University) (2005). Dan David Prize (Dan David Foundation) (2005). Emanuel Merck Lecture Prize, (Technische Universität Darmstadt/Merck) (2005). Linus Pauling Medal Award (Portland, Puget Sound and Oregon Sections of ACS) 2005. Welch Award (The Welch Foundation) (2005), U.A.A. Dhirubhai Ambani Lifetime Achievement Award (Indian National Science Academy), Priestley Medal (ACS) (2007), August-Wilhelm-von Hoffman -Vorlesung (German Chemical Society) (2007)

Memberships and Fellowships. American Academy of Arts and Sciences, National Academy of Sciences, National Academy of Engineering, American Philosophical Society, Royal Netherlands Academy of Arts and Sciences, Institute of Physics, Foreign Fellow of the Indian National Science Academy, and Honorary Fellow of the Royal Society of Chemistry. **Public Service:** National Research Council; National Science Foundation; National Institutes of Health; Department of Defense (DARPA DSRC, 1984- ; Defense Science Board (1992-2002); DTRA Treat Reduction Advisory Committee (1998-). Intelligence Science Board (2003-). **Present research interests include:** physical and organic chemistry, materials science, biophysics, complexity and emergence, surface science, microfluidics, optics, self-assembly, micro- and nanotechnology, science for developing economies, catalysis, origin of life, and cell-surface biochemistry.

David Mooney

David Mooney is the Gordon McKay Professor of Bioengineering in the Harvard School of Engineering and Applied Sciences at Harvard University. His laboratory is focused on the design and synthesis of microenvironments, or niches, that regulate the fate of either transplanted cell populations or cells already resident in tissues. These polymeric systems mimic the native extracellular matrix in their spatiotemporal control of information presentation to cells, and may find special utility in controlling stem cell populations. The applications of these systems include the regeneration of damaged or diseased tissues (tissue engineering), or the targeted destruction of undesirable tissue masses in the body. Dr. Mooney was previously a faculty member at the University of Michigan, and his education and training is from the University of Wisconsin, Massachusetts Institute of Technology, and Harvard Medical School. He is a Fellow of the American Institute of the Medical and Biological Engineering, a NIH MERIT awardee, and has received the NSF CAREER award. His inventions have been licensed by eight companies for development and he is active on industrial scientific advisory boards.

Ralph Weissleder, M.D., Ph.D.

Professor, Harvard Medical School; Director, Center for Systems Biology, Massachusetts General Hospital
Harvard University,

Dr. Weissleder is a Professor at Harvard Medical School, Director of the Center for Systems Biology at Massachusetts General Hospital (MGH), Attending Interventional Radiologist at MGH, member of the Dana-Farber/Harvard Cancer Center and Associate Member of the Broad Institute (Chemical Biology Program). Dr. Weissleder has published over 5000 peer reviewed articles, has authored and co-authored several textbooks, is currently the principal investigator of several RO1 NIH grants (including a P50 Center grant, a R24 grant, and a UO1 consortium focusing on nanotechnology) and has 20 active or pending US and international patents. He is a founding member of the Society for Molecular Imaging Research and has served as its President in 2002. His work has been honored with numerous awards including the J. Taylor International Prize in Medicine, the Millennium Pharmaceuticals Innovator Award, the AUR Memorial Award, the ARRS President's Award and The Society for Molecular Imaging Lifetime Achievement Award. He is a world leader in applying molecular imaging tools to the study of complex human diseases. He has made fundamental discoveries in early disease detection, development of nanomaterials for sensing and systems analysis. His research has been translational and several of his developments have led to advanced clinical trials.