1. PROJECT SUMMARY

Our Center develops tools to study nanoscale systems. We would like to control electrons and photons in nanostructures for future electronics and photonics, and understand how biological systems function at the nanoscale using techniques from the Physical Sciences. Three Research Clusters address these goals:

Cluster 1: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology and Medicine. Powerful new tools for manipulating and testing biological cells and tissues can be made using microfluidic systems, soft lithography, and semiconductor technology. Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

Cluster 2: Nanoscale Building Blocks makes new classes of nanostructures that exhibit size-dependent properties. We synthesize structures with unconventional shapes, as well as zero, one and two-dimensional nanostructures such as nanoparticles and nanowires. New materials are introduced, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks are promising for nanoelectronics and photonics as well as for biosensors.

Cluster 3: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons in nanostructures using custom-made scanning probe microscopes. Imaging is an essential tool for the development of nanoelectronics and photonics, and qubits for quantum information processing. New types of semiconductor heterostructures are grown for this work using Molecular Beam Epitaxy.

The **Center for Nanoscale Systems (CNS)** is a major investment by Harvard to create and maintain the facilities needed for research in his area. A new building, the **Laboratory for Integrated Science and Engineering** is under construction — it will house **CNS** facilities for imaging, nanofabrication, and materials growth. Harvard and UC Santa Barbara provide facilities to outside users through the ***National Nanotechnology Infrastructure Network***.

Connections with **Industry** are built by Harvard's **Office of Technology Development** and by the **Industrial Outreach Program**. This year our Center was funded by the **Nanoelectronics Research Initiative** of the **Semiconductor Industry Association** to develop new oxide materials for future logic switches. Many Center participants have collaborations with industry.

Our Center promotes **education** in nanoscale science and engineering and develops **human resources** at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities including REU and RET programs, a course *Applied Physics 298r – Interdisciplinary Chemistry, Engineering and Physics*, and a series of workshops.

The **Museum of Science, Boston** presents advances in nanoscience from our Center to the public in an entertaining and informative way. The Museum and the Exploratorium lead the new **National Informal Science Education (NISE) Network**.

Our Center plans to increase **Diversity** by: (1) recruiting a more diverse group of graduate students and postdocs, (2) increasing the diversity of participating faculty, (3) recruiting members of underrepresented groups by extending REU approaches, (4) introducing public school students to science & engineering, and (5) developing long-term partnerships with predominantly female and minority-serving institutions.

2. LIST OF CENTER PARTICIPANTS AND ADVISORY BOARD

(a) Center Participants

Name	Field of Research	Institution
Raymond Ashoori	Physics	MIT
Moungi G. Bawendi	Chemistry	MIT
Federico Capasso	Applied Physics & Elect. Eng.	Harvard
Kenneth B. Crozier	Electrical Engineering	Harvard
Cynthia M. Friend	Chemistry & Applied Physics	Harvard
Arthur C. Gossard	Materials	UCSB
Bertrand I. Halperin	Physics	Harvard
Donhee Ham	Electrical Engineering	Harvard
Eric J. Heller	Chemistry & Physics	Harvard
Jennifer E. Hoffman	Physics	Harvard
Marc A. Kastner	Physics	MIT
Efthimios Kaxiras	Physics & Applied Physics	Harvard
Charles M. Lieber	Chemistry & Applied Physics	Harvard
Charles M. Marcus	Physics	Harvard
Eric Mazur	Applied Physics & Physics	Harvard
Joseph Mizgerd	Biology & Public Health	Harvard
Venkatesh Narayanamurti	Applied Physics & Physics	Harvard
Hongkun Park	Chemistry	Harvard
Kevin (Kit) Parker	Bioengineering	Harvard
Pierre Petroff	Materials	UCSB
Shriram Ramanathan	Materials	Harvard
Howard A. Stone	Materials & Fluid Mechanics	Harvard
Robert M. Westervelt	Applied Physics & Physics	Harvard
George M. Whitesides	Chemistry	Harvard
Xiaowei Zhuang	Chemistry & Physics	Harvard

International Collaborators

Fabio Beltram	Physics	NEST, Pisa, Italy
Leo Kouwenhoven	Physics	Delft
Daniel Loss	Physics	U Basel
Lars Samuelson	Physics	Lund University
Hiroyuki Sakaki	Inst. of Industrial Science	U Tokyo
Seigo Tarucha	Physics	U Tokyo

Domestic Collaborators

Ali Javey	Chemistry	Harvard, Junior Fellow
Giannoula Klement	Biomedicine	Children's Hospital
Dale Larson	Biophysics	Harvard Medical School
Chinh Pham	NanoTech & Business Forum	Greenberg Traurig, LLP
Richard Rogers	Bioimaging	School of Public Health

National Laboratories

Jerrold Floro	Physics	Brookhaven
Jan Hrbek	Chemistry	Brookhaven
Julia Phillips	Physical Sciences	Sandia, CINT

Public Outreach and Education

Carol Lynn Alpert	Museum of Science, Boston
Daniel Davis	Museum of Science, Boston

Robert Graham	Harvard
Kathryn Hollar	Harvard

(b) Advisory Committee

Joanna Aizenberg	Lucent Technologies
Kenneth Babcock	Digital Instruments/Veeco Instruments
George I. Bourianoff	Intel Corporation
Steven Girvin	Yale University
Rachel Goldman	University of Michigan
Harald Hess	KLA Tencor
Evelyn Hu	University of California, Santa Barbara
Paul L. McEuen	Cornell University
Carmichael Roberts	Surface Logix
John Rogers	University of Illinois
Richard Slusher	Lucent Technologies
Ellen D. Williams	University of Maryland

3. MISSION AND BROADER IMPACT

In the following mission statement, taken from our **Project Summary**, we present the goal of our Center — to develop tools for the study of nanoscale stystems — and describe its research, education and outreach programs. The **Strategic Research Plan** presented in Section 5 describes how the three Research Clusters below address important applications, and how our investigators work together to reach these goals.

3a. Mission Statement

Our Center develops tools to study nanoscale systems. We would like to control electrons and photons in nanostructures for future electronics and photonics, and understand how biological systems function at the nanoscale using techniques from the Physical Sciences. Three Clusters address these goals:

Cluster 1: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology and Medicine. Powerful new tools for manipulating and testing biological cells and tissues can be made using microfluidic systems, soft lithography, and semiconductor technology. Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

Cluster 2: Nanoscale Building Blocks makes new classes of nanostructures that exhibit size-dependent properties. We synthesize structures with unconventional shapes, as well as zero, one and two-dimensional nanostructures such as nanoparticles and nanowires. New materials are introduced, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks are promising for nanoelectronics and photonics as well as for bio-sensors.

Cluster 3: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons in nanostructures using custom-made scanning probe microscopes. Imaging is an essential tool for the development of nanoelectronics and photonics, and qubits for quantum information processing. New types of semiconductor heterostructures are grown for this work using Molecular Beam Epitaxy.

The **Center for Nanoscale Systems (CNS)** is a major investment by Harvard to create and maintain the facilities needed for research in his area. A new building, the **Laboratory for Integrated Science and Engineering** is under construction — it will house **CNS** facilities for imaging, nanofabrication, and materials growth. Harvard and UC Santa Barbara provide facilities to outside users through the ***National Nanotechnology Infrastructure Network***.

Connections with **Industry** are built by Harvard's **Office of Technology Development** and by the **Industrial Outreach Program**. This year our Center was funded by the **Nanoelectronics Research Initiative** of the **SIA** to develop new oxide materials for future logic switches. Many Center participants have collaborations with industry.

Our Center promotes **education** in nanoscale science and engineering and develops **human resources** at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities including REU and RET programs, a course *Applied Physics*

298r — Interdisciplinary Chemistry, Engineering and Physics, and a series of workshops.

The **Museum of Science, Boston** presents advances in nanoscience from our Center to the public in an entertaining and informative way. The Museum and the Exploratorium lead the new **National Informal Science Education (NISE) Network**.

Our Center plans to increase **Diversity** by: (1) recruiting a more diverse group of graduate students and postdocs, (2) increasing the diversity of participating faculty, (3) recruiting members of underrepresented groups by extending REU approaches, (4) introducing public school students to science & engineering, and (5) developing long-term partnerships with predominantly female and minority-serving institutions.

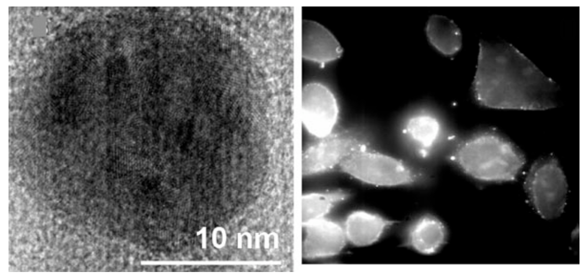

Figure 3.1. Fluorescent and Raman Active Silver Superclusters. (*left*) High resolution TEM image of a single silver supercluster. (*right*) Fluorescence image of fixed HeLa cells labeled with silver superclusters. (**Zhuang**)

3b. Advances in Fundamental Knowledge and Technology

Cluster 1: Tools for Integrated NanoBiology

This Cluster is based on the development of microfluidic and hybrid biochips and ways probe biological systems on the nanoscale. An essential tool for NanoBiology is the ability to image and manipulate the inside of living cells. We feature two recent achievements by **Xiaowei Zhuang** and **Kit Parker**.

A grand challenge in biological imaging is to image individual biomolecules and their interactions *in vivo*. **Xiaowei Zhuang** is developing highly fluorescent and Raman-active silver superclusters for this purpose. These particles are fluorescent, allowing optical imaging of their location, and they have giant Raman enhancement that should allow chemical sensing.

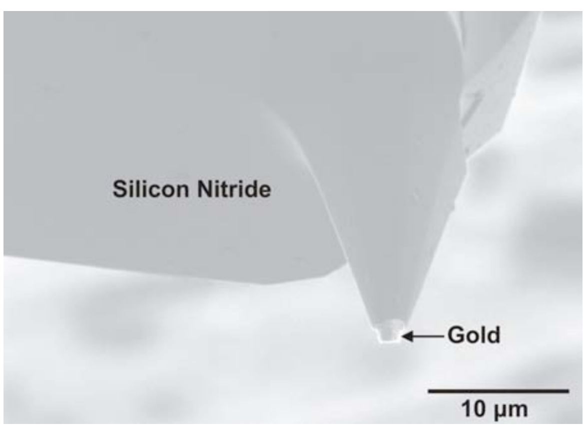

Figure 3.2. SEM image of a conductive AFM cantilever tip for cellular nanosurgury. Selective etching exposes an underlying gold layer at the cantilever tip, allowing for local delivery of current during electroporation experiments. (**Parker)**

Figure 3.1 shows (*left*) a TEM image of a single Ag supercluster and (*right*) a fluorescence image of fixed HeLa cells labeled with Ag superclusters. **Zhuang** plans to functionalize the surface of these superclusters for specific bio-molecules, and use them as labels to track individual protein and RNA molecules in live cells.

Kit Parker is developing an experimental system for image-guided cell nanosurgury. An atomic force micro-scope (AFM) is coupled to an inverted optical microscope with a high-speed camera. A specially prepared AFM tip, shown in Figure 3.2, acts as the scalpel. The small exposed gold region at the end will be used to electroporate cells for the delivery of proteins or cell organelles.

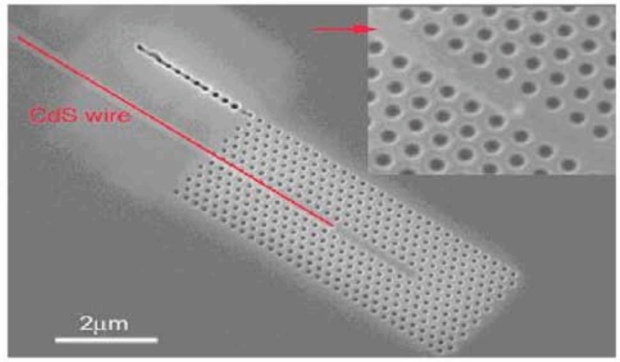

Figure 3.3. Hybrid nanowire/photonic device: A CdS light-emitting nanowire is embedded in a silicon nitride photonic crystal that can guide the light around a chip. (**Capasso** and **Lieber**)

Cluster 2: Nano Building Blocks

This cluster is developing new types of building blocks. **Bawendi** is developing composite nanoparticle bio probes that contain both fluorescent and magnetic nanoparticles, **Park** and **Lieber** are synthsizing nanowires from new materials, and **Ramanathan**, a new member of the Center, is developing oxide semiconductors for nanoelectronics. **Lars Samuelson** (Lund Univ., Sweden) recently joined the Center as an international collaborator. In the highlights here we feature two interesting applications of semiconductor nanowires.

Charles Lieber and **Federico Capasso** have developed hybrid nanowire/photonic devices. Figure 3.3 shows an image of a CdS light-emitting nanowire that is embedded in a silicon nitride photonic crystal. The photonic band gap strongly confines light to the wire, reducing the laser threshold and achieving extremely narrow divergence. In this way the light emitted from the nanowire can be guided around a chip, making possible future generations of planar light wave-guiding circuits.

Robert Westervelt and **Lars Samuelson** used a cooled scanning probe microscope (SPM) to image an InAs quantum dot grown in an InAs/InP nanowire, as shown in Figure 3.4. By switching the alloy from InAs to an InP barrier region during growth, Samuelson's group can grow small, high-quality InAs quantum dots. With a gate, the number of electrons on the dot can be reduced to zero. For imaging, the SPM tip acts as a movable gate that can locate the position of the quantum dot, and change the number of

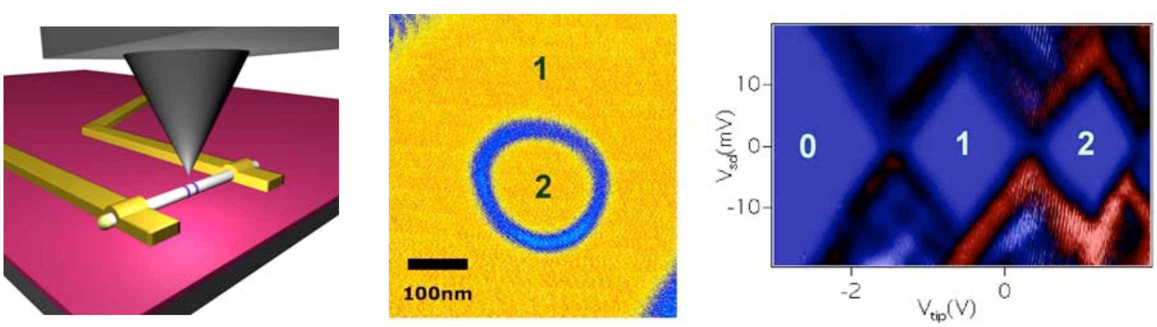

Figure 3.4. (*left*) Illustration showing an SPM tip acting as a movable gate over an InAs quantum dot in an InAs/InP nanowire. (*center*) Experimental SPM image at 4.2 K as the tip is scanned above the InAs quantum dot — tip locations for 2 and 1 electrons on the dot are indicated. (*right*) Coulomb blockade diamonds for 0, 1 and 2 electrons on the InAs quantum dot. (**Westervelt** and **Samuelson**)

electrons. This approach is promising for future studies of single and coupled quantum dots in heterostructure nanowires.

Cluster 3: Imaging at the Nanoscale

This cluster is developing new approaches to visualizing the behavior of electrons and photons inside nanostructures. **Ashoori** is investigating new materials using charge-sensing imaging, **Nararyanamurti** is developing Ballistic Electron Emission Luminescence for electronic photonics of nanostructures, and **Eric Heller** is using sophisticated theory to understand the sources of contrast in SPM images. In these highlights we describe a new approach to scanning near-field optical microscopy (SNOM), and the design of a sensitive magnetic AFM.

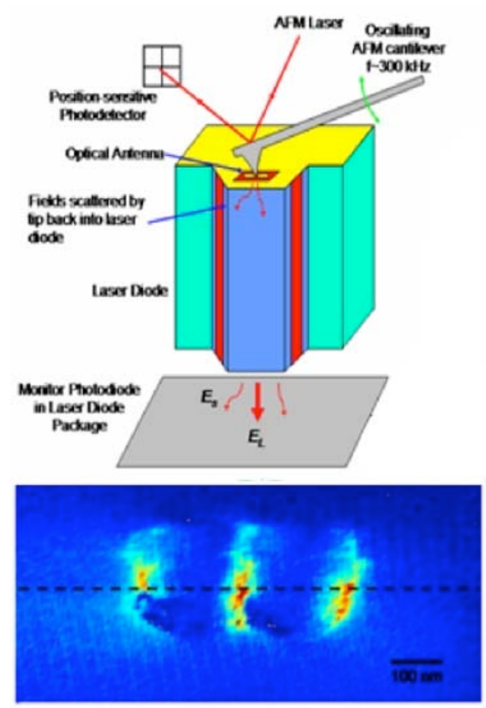

Figure 3.5. Near-field image of an optical antenna on the facet of a diode laser showing an intense electric field. (**Crozier** and **Capasso**)

Kenneth Crozier makes robust conical tips for SNOM with a microlens on top using MEMS fabrication techniques. With **Federico Capasso**, **Crozier** has developed an optical antenna that will be able to sharpen the spatial resolution of these tips considerably, to deeply subwave-length values. Figure 3.5 shows a near-field image of intense, sharply focused fields in an optical antenna in the form of two narrow bars that was fabricated on the facet of a diode laser. The width of the bright spots is less than 50 nm. This approach has considerable promise for robust, high-resolution SNOM tips.

Jennifer Hoffman is building custom-cooled scanning tunneling and atomic force microscopes. Figure 3.6 shows the design for a cooled magnetic force AFM with 10-nm spatial resolution and sub-pN force resolution. This instrument will be used to image forces from magnetic vortices and magnetic features of nanostructures.

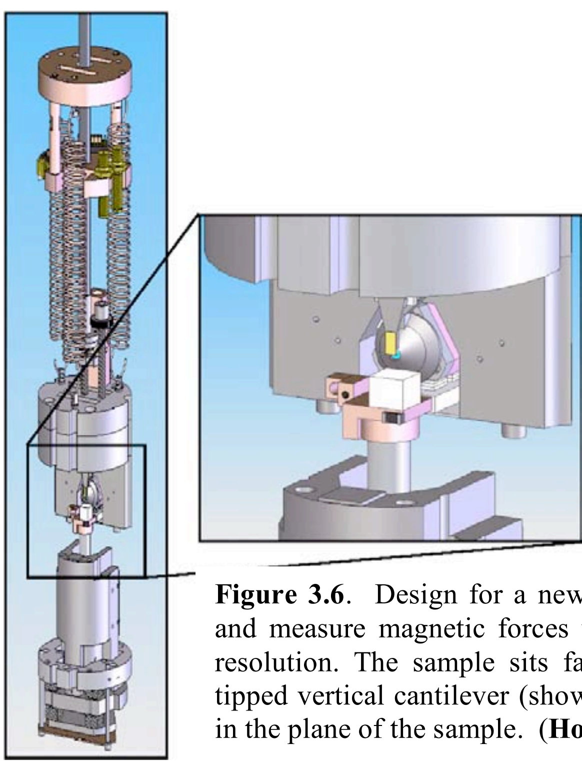

Figure 3.6. Design for a new cryogenic magnetic force microscope to detect and measure magnetic forces with 10-nm spatial resolution and sub-pN force resolution. The sample sits face-up on the white surface, while a magnetic-tipped vertical cantilever (shown in yellow) is used to measure magnetic forces in the plane of the sample. (**Hoffman**)

3c. Advances in Education

Education is an important mission of our Center. As the coordinator, **Kathryn Hollar** has done an outstanding job organizing our programs for education, outreach and diversity. A description of our activities are presented below in Section 3e.

Last year the NSF selected the Museum of Science, Boston, the Exploratorium in San Francisco, and the Science Museum of Minnesota to form a national **Nanoscale Informal Science Education (NISE) Network** of multiple science and research institutions. **Carol Lynn Alpert** and Larry Bell are the PI's at the Museum of Science. Our NSEC has collaborated with **Carol Lynn Alpert** since 2001 to bring ideas from nanoscience to the public, in which the Museum is expert. The NISE Network will allow us to reach a nation-wide audience through entertaining and informative exhibits and presentations. The Scientific Advisory Board of the NISE Network includes NSEC faculty **Eric Mazur**, **George Whitesides**, and **Robert Westervelt**, who is its Chair. We look forward to working closely with the NISE Network to bring the excitement of nanoscience to the public.

Applied Physics 298r is a course at Harvard that is run every other year by our NSEC. The aim is to provide an introduction to Nanoscale Science and Engineering to undergraduates and graduate students. The Center's faculty present a series of tutorial lectures about their field of research, following an overview by the Director. The lecture slides are openly available on the course's website. AP298r was held last in Spring 2005, and is scheduled again for Spring 2007. It gets excellent reviews. Section 7, *Center Diversity* and Section 8, *Education* present the Center's programs in these areas.

3d. Advances in Industrial Collaborations

Harvard is making important advancements in connecting academic research with industry. In May 2005 the University appointed Isaac Kohlberg as Associate Provost and chief technology development officer to oversee the development of new technologies based on discoveries at Harvard. The **Office of Technology Development** conducts a broad range of activities ranging from reporting inventions, to helping faculty connect with industry. The Center works with Oded Hecht of this office. He has become quite familiar with the research of our investigators, and learns about advances that may have industrial applications. Senior executives from major companies are brought to Harvard to learn about new research and possible collaborations. The active approach promises to be very effective.

In Fall 2005 our Center was awarded a supplement from the **Nanoelectronic Research Initiative (NRI)** of the **Semiconductor Industry Association (SIA)**. The SIA recognizes that technology beyond CMOS will be needed for logic switches in the future, and it is supporting research at universities to help discover the right approach. Our Center is closely related to these goals, with our emphasis on nanowire devices, nanoelectronics and nanophotonics. The first day of the Center's international *Frontiers in Nanoscale Science and Technology* workshop held in San Francisco on January 26–28, 2006 was devoted to industry with talks by George Bourianoff (Intel), Robert Doering (TI), Pushkar Apte (SIA), about the future of electronics, and researchers Phaedon Avouris (IBM), Lars Samuelson (Lund Univ.), **Shriram Ramanathan** (Harvard) and Hongjie Dai (Stanford), about nanotubes, nanowires and nanoelectronics, and Yasuhiko Arakawa (U Tokyo) and **Federico Capasso** (Harvard) about nanophotonics. The mix was quite successful. We look forward to expanding our interactions with NRI and the semiconductor industry in the future.

3e. Current and Potential Impact of NSEC on Education, Workforce Development, Diversity, and Society

The NSEC based at Harvard University has a wide repertoire of activities that contribute to the public understanding of nanoscale science and engineering, encourage participation of underrepresented groups at all levels of education, enhance the infrastructure of research and education at all education levels both locally and internationally.

The collaboration between the NSEC based at Harvard and the Museum of Science, Boston, has been a model for interaction between an informal science organization and a research and higher education organization. This relationship has informed thousands of people of the risks and benefits of nanoscale science and engineering to society through multimedia, television, museum visits, and public presentations; it has also helped practicing scientists and engineers to engage the public in discussions of the *realistic* risks and benefits of this new technology. Participation in the newly formed NISE-Network will not only deepen this level of understanding by researchers of how to effectively listen and respond to public concerns regarding nanoscale science and engineering research, it will also allow us to disseminate these new communication models across a wide network of collaborators.

Through our long-standing relationship with the Cambridge Public Schools, a school system with a minority majority population, we introduce over 300 7th grade students each year to scientific research being conducted at Harvard University. Community activities with Cambridge Public Schools impacted another 250 students and their families. The Research Experiences for Teachers program allows us to develop sustained and close relationships with teachers in the Cambridge Public Schools and surrounding school systems. Modules developed through the RET program have been disseminated to over 150 teachers through teacher workshops. As we continue to develop new modules through the RET program, we expect to impact a wider audience through continued dissemination locally and nationally. In all our K12 outreach efforts, we strive to partner with school systems and programs that have a significant population of underserved students.

The REU program is one of our flagship programs for preparing a diverse pool of future leaders in science and engineering. Through aggressive recruiting efforts, 30–40% of our participants each year are from underrepresented groups. Through professional development activities such as presentation and writing skills and mentor training, we not only prepare the participants and mentors scientifically, but help them develop skills that will enhance their careers in science and engineering.

In 2005–2006, local and international workshops and collaborations have brought together over 500 practicing scientists, engineers, as well as leaders in business and government, to discuss new directions in nanoscale science and engineering. For example, the Frontiers in Nanoscale Science and Engineering workshop and Industrial Outreach Program at Harvard are annual events that continue to provide opportunities for our faculty, graduate students and postdoctoral researchers to share research results with a wide array of institutions.