Up Close: Materials Research Science and Engineering Centers—U.S. National Network for Materials Research

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Introduction

In 1994, the U.S. National Science Foundation (NSF) established Materials Research Science and Engineering Centers (MRSECs). The goal was to provide support for interdisciplinary materials research and education of the highest quality while addressing fundamental problems in science and engineering that are important to society. The centers are expected to undertake materials research of a scope and complexity that would not be feasible under traditional funding for individual research projects or small groups. Centers are funded for a limited period of time—currently five years—after which they can re-compete against new proposals. In 1994, MRSECs were established at 11 universities throughout the country. Two years later, 13 new centers were established in a second round of funding. Additional competitions were completed in 1998, 2000, and 2002. As of April 2002, there were 29 MRSECs.

Materials science and engineering is an inherently interdisciplinary field. When it began, the field could be characterized as the application of chemistry and physics to the solid state; but more recently, it has been recognized that the concepts developed from this work, which were and remain relevant in fields such as metallurgy, semiconductor science and technology, and polymer science, could also be useful for problems in fields such as biology and geology. At the same time, many computational methods have been developed that simulate the behavior of materials, and the focus of understanding and application has continually shifted with time from the bulk and mesoscopic scales toward the nanoscale. Because of the great breadth of the field, which can be seen through the examples shown in Figure 1, NSF has for many years provided group funding to encourage interdisciplinary activity.

The current MRSECs are the descendents of the Interdisciplinary Laboratories started by the Advanced Research Project Agency in the early 1960s. In 1971, these laboratories were transferred to NSF and were renamed Materials Research Laboratories (MRLs). These MRLs were followed by the Materials Research Groups (MRGs) of the 1980s and early 1990s which, in turn, were followed by the MRSECs. However, the MRSECs differ in several important ways from their predecessors. Although world-class research still lies at the core of the MRSECs and the centers maintain state-of-the-art shared facilities that can be used by other universities and industries, these new centers have an expanded scope. The responsibility of technically trained experts to educate the public at large on technical matters and to encourage young people to enter this field is emphasized through the large number of education outreach programs run by these centers. Another emphasis of these centers is the interaction between universities and

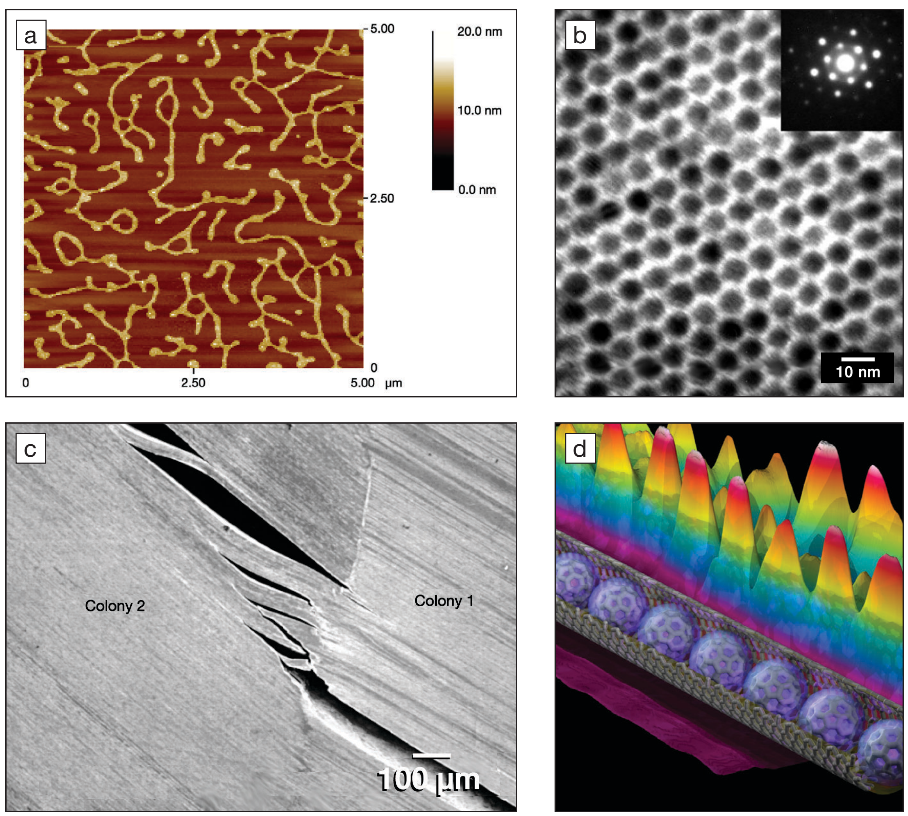


Figure 1. Examples demonstrating the breadth of research in the Materials Research Science and Engineering Center (MRSEC) program. (a) A spinodal self-assembly of nanocrystals resulting from van der Waals interactions, obtained at the Columbia University MRSEC. (b) Self-assembled Fe-Co-Pt nanoparticles studied as part of research at the University of Alabama MRSEC. (c) Cracks propagating in lamellar TiAl examined at the Brown University MRSEC. (d) Low-temperature ultrahigh-vacuum scanning transmission electron microscopy image of nanotube "peapods" studied at the University of Pennsylvania MRSEC.

industries. These centers work closely with a number of industries to define important areas of research and to transition ideas developed in the university into practice. These transitions occur through the strong industrial ties that are part of each center.

The MRSECs represent a national network to facilitate materials research, education, and practice throughout the United States. They are a resource that can be used by elementary and secondary schools, colleges and universities, and industries. The purpose of this article is to describe the activities of these centers and, through the examples given, to encourage their use. Detailed information on the topics discussed (and much more) can be found at www.mrsec.org. This Web site for the MRSEC program has links to all of the individual centers.

Research

At the heart of these centers is research in materials science and engineering. Within each center, the research is broadly organized into Interdisciplinary Research Groups (IRGs). Each of these IRGs has a focused research theme. In this section, several of the research programs will be highlighted.

The study of microstructure and its effect on properties remains central to materials science. In some areas, the goal is to understand microstructure at the atomic level and to make use of state-of-the-art electron microscopy or other techniques to reach this goal. However, another important goal is to obtain three-dimensional (3D) microstructures of a material in order to achieve a through-thickness view. Although the resolution used in these studies may be somewhat lower than that used in atomic-scale studies, the wealth of information obtained by examining the interrelationship of different elements of the microstructure in three dimensions provides great insight into many important problems. One example of this type of work is being performed at the MRSEC at the State University of New York, Stony Brook, that is focused on thermal-spray research. This center has strong industrial ties and works to understand and improve current methods for thermal spray and to develop new methods of thermal-spray deposition. A crucial element of the understanding that leads to improved thermally sprayed products is determining the nature and distribution of the defects in the structure. These include sizes and surface-area distributions of features such as intrasplat cracks, intersplat lamellar pores, and globular pores. This information can then be used to define the complex relationships between microstructure and spray-process conditions.

One novel way in which researchers at this MRSEC have probed the 3D microstructure is through the use of x-ray computed microtomography (CMT). CMT is an imaging technique that provides cross-sectional views of the interior of an object. The CMT image represents point-to-point linear-attenuation coefficients in a slice to discriminate between thickness and density changes. Density maps are obtained by reconstructing the sequential cross-sectional slices. Thus, CMT allows studies of difficult-to-analyze microstructural features. Figures 2a and 2b show CMT micrographs, at a resolution of about 1 μm, in plasma-sprayed partially stabilized zirconia coatings, which are used as thermal-barrier coatings in gas turbines. Figure 2a shows the globular pore structure in the as-sprayed coating, and Figure 2b shows the loss of these pores through sintering during thermal cycling. Thus, the microstructure can be probed to determine how heat treatments can lead to the elimination of defects.

Researchers in the MRSEC at Carnegie Mellon University (CMU) are also working on 3D representations of microstructures. In particular, they have examined the 3D grain-boundary network that exists in materials. By combining automated digital microscopy and computer analysis of image data, the researchers recently reconstructed the 3D structure of a 5×10^6-μm^2-grain-boundary area in a cubic millimeter of a polycrystalline ceramic, MgO. Results show that special types of grain boundaries occur far more frequently than others and that these boundaries are not predicted by currently accepted theories. Figure 2c plots the standard projection on a [001] pole figure of the population of grain-boundary planes at two fixed misorientations (5° about ⟨111⟩ on the left and 60° about ⟨111⟩ on the right). The peaks and minima in the function illustrate that specific planes are favored over others and, thus, that there is a high density of special grain boundaries. With the ability to characterize the grain-boundary network with this level of detail, it may now be possible to understand how these special boundaries influence the properties and processing of solid polycrystalline materials.

Biological and soft materials represent a strong new research thrust in many of the centers. This research often leads to material design at the atomic or even electronic level. For example, researchers at the Cornell University MRSEC have developed molecular transistor devices that may enable the manipulations of single electrons on the smallest possible device length scale in which an electron hops on and off a single atom between two contacts. This device has been achieved by nanofabricating gold electrodes separated by a very narrow gap, as shown in Figure 2d. A single molecule containing a cobalt atom in a well-designed bonding configuration is then incorporated into the gap. The electrical characteristics of the transistor can be varied systematically by making chemical changes to the molecule. This work represents two significant steps forward in the field of molecular electronics: the ability to design the electronic states of a molecular device using chemical techniques and the ability to measure the properties of individual molecules.

In a joint effort between the MRSECs at the University of Minnesota and the University of Pennsylvania, vesicles shown in Figure 2e were made from amphiphilic diblock copolymers and characterized by micromanipulation. The average molecular weight of the various polymers studied are at least several times greater than that of typical phospholipids in natural membranes. Although the membrane elastic moduli of the polymersomes (polymer-based liposomes) fall within the range of lipid membrane measurements, the giant polymersomes proved to be an order of magnitude or more tougher, sustaining far greater areal strain before rupture. The polymersome membranes were at least 10× more impermeable to water than common phospholipid bilayers. The results suggest a new class of synthetic thin-shelled capsules based on synthetic block-copolymer chemistry.

Studies of the electronic and magnetic properties of materials continues to be a central research theme in many IRGs. Strain-driven self-assembly of semiconductor nanostructures holds promise as a basis for quantum device fabrication. Research in several laboratories has shown that for epitaxial island formation in the Si/Ge system, small islands grow predominantly with {105} lateral faces. At Brown University, researchers have developed a framework, based on the evolution of stepped crystallographic surfaces, to understand the physical origins of this surface orientation and to show the intimate connection between strain and surface reconstruction that leads to this surface orientation.

One research group in the MRSEC at the Massachusetts Institute of Technology (MIT) is working on the design and fabrication of microphotonic materials and structures. Such materials allow an unprecedented level of control over the confinement and propagation of light at dimensions that enable the design and eventual integration of a large number of micro devices on a single chip. This group has recently utilized a photonic crystal to dramatically improve the light output of semiconductor light-emitting diodes (LEDs). This goal has been accomplished by explicitly controlling the spontaneous emission into the guided modes of the device. The basic idea is to exploit three important characteristics of two-dimensional periodic photonic-crystal slab geometries. The first is the possibility of designing a photonic bandgap within a range of frequencies for the in-plane guided modes of the system. The second is the possibility of coupling to resonant modes above the bandgap. The third is an intrinsic upper cutoff frequency for waveguiding in the plane. In all cases, these frequency ranges can be used to prevent radiation from propagating into the dielectric slab, thus forcing the light into the light-cone of the air region. The microphotonics team has recently designed a prototype photonic-crystal LED

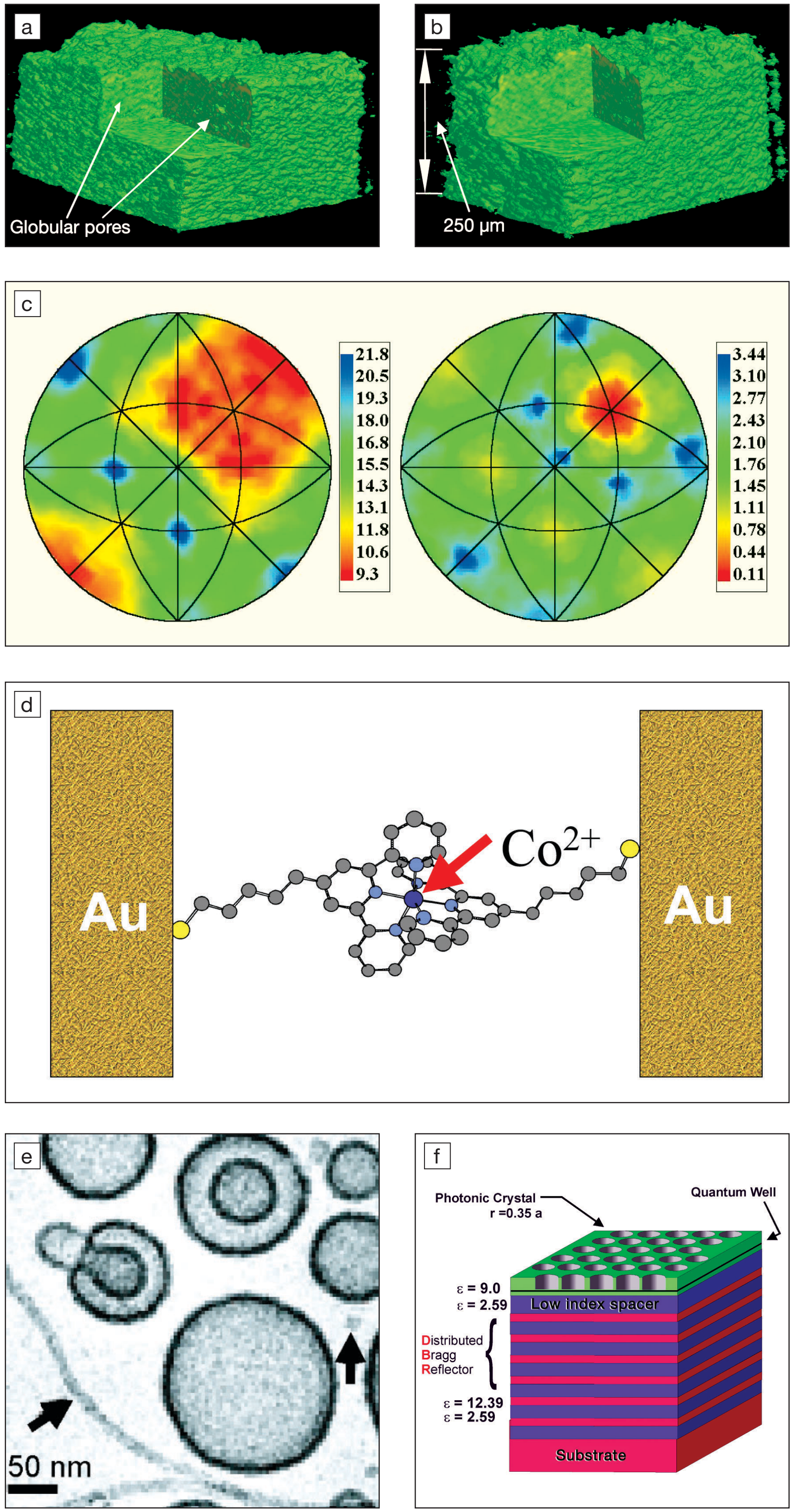


Figure 2. Research is at the heart of the Materials Research Science and Engineering Centers.

(a)–(b) Work done at the MRSEC on thermal-spray processing at the State University of New York, Stony Brook. X-ray computed microtomography results show microstructural features observed in plasma-sprayed, partially stabilized zirconia coatings, used as thermal-barrier coatings in gas turbines. The resolution is 1–1.5 μm. (a) Globular pore structure in an as-sprayed coating. (b) Sintering effect during thermal cycling at 1150°C for a total of 10 cycles.

(c) A standard projection on [001] of a 3D structure of the grain boundaries in polycrystalline MgO that was fabricated at the Carnegie Mellon University MRSEC. The projection illustrates the population of grain-boundary planes at two fixed misorientations (5° about ⟨111⟩ on the left and 60° about ⟨111⟩ on the right). The units are in multiples of a random distribution. The peaks and minima in the function illustrate that specific planes are favored over others.

(d) A molecular transistor in which a single electron can hop on and off a cobalt atom; developed at the Cornell University MRSEC.

(e) Research performed jointly by the University of Minnesota and the University of Pennsylvania MRSECs. Cryo-transmission electron microscopy images of vesicles (main structures), wormlike micelles (left arrow) and spherical micelles (right arrow) formed from poly(ethyl oxide)–poly(ethyl ethylene)PEO-PEE diblocks in water.

(f) Schematic of a photonic-crystal light-emitting diode. This device was made at the Massachusetts Institute of Technology MRSEC.

to the imposed fabrication and testing requirements (Figure 2f). This LED was designed to operate in the resonant-mode regime and has now been fabricated, tested, and found to possess integrated extraction efficiencies that are eightfold greater than the control LED.

These brief summaries describe only a few of the interdisciplinary research programs. Table I provides a guide to all of the research areas in these centers and specific achievements that have been accomplished there. With this information and the MRSEC Web site (www.mrsec.org), one can explore the broad range of research that is ongoing through the MRSEC program.

Education Outreach

Educational activities are an integral component of each MRSEC. Conducted through various partnerships, these activities greatly expand MRSEC research into the community, making it accessible to teachers, students, and nontechnical audiences. Since materials research involves a combination of diverse disciplines in science and engineering, such efforts by MRSECs are ideally suited to enhance science literacy; simultaneously, the centers help to recruit a diverse group of talented students into the field. The community participants, likewise, benefit by new opportunities for professional development. This section describes some of the outreach programs: ones in which students and teachers from K–12 come to the center to work, and ones in which university faculty and students work with community groups, especially with local schools.

Nearly every MRSEC conducts a program called Research Experience for Undergraduates (REU). This program introduces undergraduate students to the field of materials science as they gain valuable research experience during the summer. Such experience is especially valuable for students at colleges with limited research programs. The program may also help students recognize their aptitude for graduate-level research and, thus, affect their career paths. REU students typically work with faculty and research staff at a MRSEC site on a short-term research project. Often they are part of a community of REU students on a campus and have opportunities to participate in organized social and professional-development activities. For example, the students at Brown University become part of a larger group of summer interns through the Leadership Alliance, a group that helps place underrepresented minority students in summer programs at major research universities. As part of this activity, the participants present papers at the end of the summer at a national conference that encompasses many areas of research, both technical and nontechnical. In addition, faculty from other universities may participate in summer programs. At the University of Minnesota MRSEC, graduate student Rick Schroden and Nagalingam Balakrishnan of United Tribes Technical College worked during a summer program to develop a laboratory guide titled *An Inverse Opal Photonic-Crystals Laboratory Guide*, which provides step-by-step procedures for the synthesis of crystals based on macroporous metal oxides: www.mrsec.umn.edu/mrsec/main.shtml. During the summer, Anna Gopher, one of Balakrishnan's students, worked with him at the University of Minnesota on the research project (see Figures 3a and 3b, p. 643).

In addition to bringing undergraduate students to the university for summer research, many MRSECs have Research Experience for Teachers (RET) programs which involve middle school and high school science teachers in research projects. Within this program, participants develop curricular materials to use in their classrooms. While most of the projects occur during the summer, in some cases teachers continue their participation into the academic year. The teachers may be compensated with a stipend, professional-development credits, or graduate school credit; these benefits vary among the MRSECs.

As a result of working in a research environment, the teachers are better able to communicate the content, process, and excitement of science to their students. During their summer experiences, teachers become familiar not only with the techniques and procedures of forefront research laboratories, but also with other teachers as well as scientists and engineers at a variety of career stages. Their experience provides them with a network of professional contacts that can enable them to sustain and expand upon their experiences. Likewise, MRSEC personnel gain experience in communicating their research and in building the strength of the research community. One example of a RET program involves teacher Debbie Desser, who worked with Giacinto Scoles, a professor at Princeton University (see Figures 3c and 3d).

In many programs, MRSEC faculty, staff, and students go to the schools to work with teachers and students or supply materials to the schools to aid in curriculum development. With their collectively broad knowledge of physics, chemistry, biology, and engineering, MRSEC researchers aid in the establishment of interdisciplinary connections while assisting in curriculum development and helping to meet the standards-based curriculum reform emphasizing hands-on learning and inquiry. For example, Cornell MRSEC scientists have provided Spanish-language science education (see Figure 3e), while Princeton MRSEC researchers have been helping teachers in New Jersey public schools implement new inquiry-based experimental kits and have provided background and supplementary material. MRSEC scientists have also developed workshops that support continuous professional development for teachers. Several MRSECs provide instructional materials on various subjects in materials research. The Materials World Modules Program at the Northwestern University MRSEC has developed nine inquiry-based modules on topics such as composites, biosensors, polymers, and sports materials that have been used by 15,000 students throughout the United States. The University of Wisconsin—Madison MRSEC has developed instructional materials around its theme of nanostructured materials, such as their hands-on kit and booklet called "Exploring the Nanoworld," designed for nontechnical audiences. An example is shown in Figure 3f.

Some MRSECs are participating in "Ask a Scientist" programs, including a few specifically designed to serve the K–12 teaching community. For example, the University of California, Santa Barbara (UCSB) ScienceLine Internet project (www.scienceline.ucsb.edu) links UCSB researchers with K–12 schools and the community. Students and teachers post science-related questions by e-mail and receive one or more responses from scientists in a variety of fields. An archive of past questions and answers may be found at the Web site www.ccmr.cornell.edu/ask/index.html. The teachers are guaranteed an answer within one week. Cornell's MRSEC publishes a weekly "Ask A Scientist" column in its local newspapers, the *Ithaca Journal* and the *Binghamton Press and Sun-Bulletin*.

In addition to working with schools, some MRSECs have partnered with museums and science centers to provide outreach to the public. The University of Chicago MRSEC has worked with the Chicago Museum of Science and Industry, and is assisting the Ontario Science Center (Toronto) in the design of a large, mobile exhibit dealing with the field of materials science that is scheduled for a tour across North America, starting in Toronto. A similar travelling exhibit on modern materials is being developed by The Pennsylvania State

Table I: Research Topic Areas within the Materials Research Science and Engineering Center System.*

Research Group	Research Topic Area	Center
Biomolecular and Biomimetic Materials	Biomaterials microstructures, biomimetic synthesis, interfaces, porous materials	University of California at Santa Barbara
	Biosynthesis of macromolecular materials	California Institute of Technology
	Bio-interfacial science	University of Chicago
	Interfaces between synthetic and bio systems	Harvard University
	Artificial tissues	University of Minnesota
	Functional biomolecular materials	University of Pennsylvania
	Bio-inspired composites	Princeton University
	Biomolecular membranes	Stanford University—IBM/UC—Davis
	Nanostructured materials as interfaces to biology	University of Wisconsin—Madison
Coatings and Ceramics	Complex oxides for photonics	Northwestern University
	Multifunctional complex oxides	University of Pennsylvania
	Thermal-spray coatings, synthesis of oxides	State University of New York at Stony Brook
Condensed-Matter Phenomena	Mesoscopic self-assembly, colloids, polymers, tunable quantum materials	University of Chicago
	Ferroelectric liquid crystals	University of Colorado
	Doped Mott insulators	Massachusetts Institute of Technology
	Collective phenomena in restricted geometries	The Pennsylvania State University
	Phases and excitations in low-dimensional electronic materials	Princeton University
Magnetic and Ferroelectric Materials and Structures	Thin-film and particulate materials for ultrahigh-density data storage	University of Alabama
	Polarization dynamics in ferroelectric thin films, metal oxides with high spin polarization	University of Maryland
	Giant magnetoresistance, diamond, magnetic and electronic sensing	Michigan State University
	Magnetic heterostructures, spintronics	University of Minnesota
Nanostructures	Structural integrated films containing nanoparticles	Columbia University
	Electron and spin transport in nanostructured materials, dynamic mechanical properties of nanoscale materials	Cornell University
	Electronic microsystems	Harvard University
	Nanostructures with enhanced magneto-electronic effects	The Johns Hopkins University
	Carbon nanotubes, synthesis, and processing	University of Kentucky
	Nanostructured materials for chemical and biological sensing, polyelectrolyte nanocomposites and structures	Northwestern University
	Semiconductor nanostructures—growth and characterization; nanoscale interfaces and magneto-electronics	Universities of Oklahoma/Arkansas
	Carbon nanotube materials	University of Pennsylvania
	Nanoscopic design, quantum dots, surfaces	University of Wisconsin—Madison
Mechanics of Materials	Micro- and nanomechanics of electronic/structural materials	Brown University
	Bulk metallic glasses and composites	California Institute of Technology
	Grain boundaries, metals/ceramics; simulations	Carnegie Mellon University
	Micromechanical systems	Harvard University
Nonequilibrium Phenomena	Strongly nonequilibrium phenomena in complex materials	University of California at Santa Barbara
	Macroscopic dynamics of materials	University of Chicago
	Photonic sensing and turbulent flow	Michigan State University
Organic Systems and Colloids	Microscale soft materials	University of Pennsylvania
	Organic molecular-beam epitaxy and metalorganic chemical vapor deposition, thin films, quantum structures	Princeton University
Polymers	Mesoscopic macromolecular structures	University of California at Santa Barbara
	Nanoscale polymer–inorganic hybrid materials	Cornell University
	Controlled interfacial interactions, polymers in supercritical fluids	University of Massachusetts
	Microstructure and mechanical performance of polymers	Massachusetts Institute of Technology
	Molecular mechanisms of environmentally benign polymer processing	Northwestern University
	Amphiphilic polymers: self-assembly	Princeton University
	Macromolecular architectures	Stanford/IBM/UC—Davis
	Polymers at engineered interfaces	SUNY at Stony Brook—Garcia Polymer
Semiconductors and Photonics	Wide-gap films	Arizona State University
	Microphotonic materials and structures	Massachusetts Institute of Technology
	Chemical vapor deposition growth; materials integration on silicon	University of Wisconsin—Madison
Synthesis and Processing	High-pressure synthesis	Arizona State University
	Fundamentals of energetic surface processing	Cornell University
	Advanced oxides and fuel cells	University of Houston
Surfaces, Layers, and Interfaces	Oxide glasses—surfaces and thin-film interfaces	Cornell University
	Surface nanostructures, dynamics	University of Maryland
	Critical grain boundaries in high-temperature superconductors for applications	University of Wisconsin—Madison

*Reproduced from the Materials Research Science and Engineering Center (MRSEC) Web site www.mrsec.org/centers. Access the Web site to view research highlights.

University MRSEC in collaboration with the Franklin Institute Science Museum in Philadelphia, while the University of Wisconsin—Madison MRSEC is partnering with the Discovery World science center in Milwaukee to create new exhibits and K–12 teaching materials based on nanotechnology.

In summary, a continually increasing variety of innovative programs in education and outreach remain a cornerstone of the MRSECs. As the MRSEC program enters its second decade, the efforts of the 29 centers in this direction have determined what methods provide maximum leverage of the finite resources and which programs are most efficient. Such programs will continue to be of paramount interest because educating the general public and future generations about the interdisciplinary nature of materials research will not only lead to a scientifically and technologically literate public but also aid in providing the field with its future researchers.

Industrial Interactions

Many industrial research laboratories continue to downsize basic research, while academic laboratories exhibit an accelerating interest in connecting fundamental research to real-world problems. These trends are creating an environment in which collaboration between these two sectors is becoming increasingly important for the advancement of key technologies and the achievement of national science and engineering goals. Given the central role of materials in the industrial sector, MRSECs provide a natural home for academic-industry interactions that have an impact on a large portion of commercially relevant research. NSF encourages each MRSEC to develop such interactions.

A survey of the industrial outreach programs coordinated by the 29 MRSECs reveals numerous companies and national and international laboratories engaged in collaborative research, the companies ranging from small start-ups to large corporations (Table II, p. 645). Because the research emphases and institutional cultures differ for each MRSEC and each company, MRSEC industrial outreach programs are individually tailored to optimize collaborations.

Interactions of academic research laboratories with the industrial sector are generally viewed in terms of technology transfer or knowledge transfer. Although any distinction between these terms may seem a question of semantics, they differ with respect to expected outcomes and deliverables. Technology transfer is typically associated with the development of a product or concept closely associated with a specific commercial device and is commonly accompanied by strict intellectual-property and inventor agreements. Knowledge transfer, on the other hand, emphasizes the transmission of ideas and concepts that contribute to a company's (or even an entire industry's) understanding of principles that afford improvements in commercial products or stimulate new inventions, although sometimes in less tangible ways. Collaborative interactions that revolve around knowledge transfer often are performed in an unrestricted manner in which ideas are exchanged in both directions and, in some cases, among several companies in consortium-like arrangements. NSF officially endorses *knowledge* transfer, but does not discourage other, more directed interactions. Recognizing that a "one size fits all" model is inherently unworkable, NSF encourages the development of industrial outreach programs that are best suited for each center. Consequently, most MRSECs have flexible arrangements designed to accommodate diverse company policies and the fluidity of the industrial sector.

The various MRSEC industrial outreach programs run the gamut from technology-transfer and knowledge-transfer arrangements to focused efforts with a few companies (as well as broad portfolios containing numerous member companies); start-up companies emerging from MRSEC research; and even programs that bring companies, MRSEC graduate students, and MBA students together to solve specific process and product problems. A common characteristic of all of these arrangements, however, is the extension of the impact of MRSECs beyond their university boundaries and into the industrial sector. Because of their interdisciplinary character and group-based infrastructure, MRSECs can provide opportunities that can be incompatible with conventional academic research settings. Collaboration with interdisciplinary centers like MRSECs brings substantial benefits to industrial partners, including

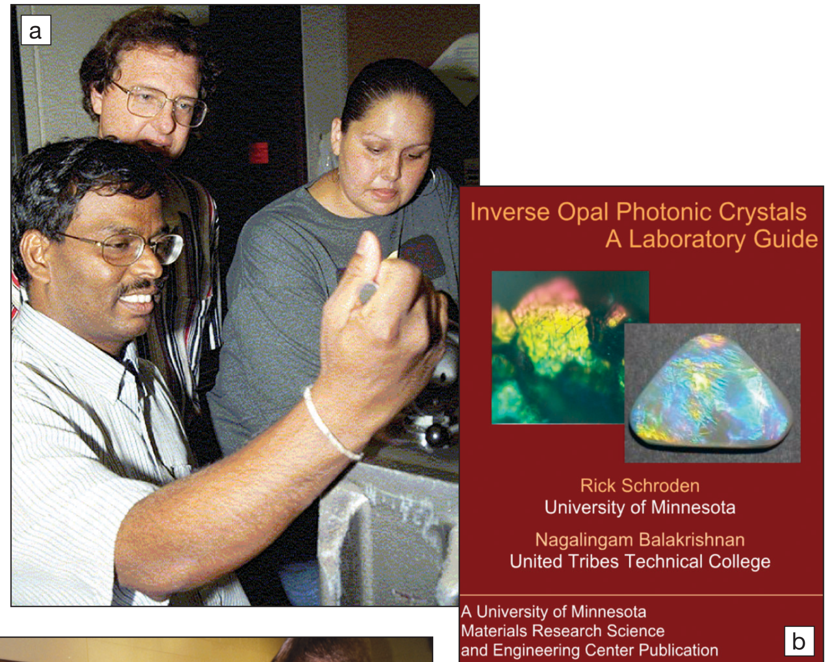
- cutting-edge fundamental research that complements research in the industrial sector;
- faculty, students, and postdocs skilled in critical and emerging research areas;
- state-of-the-art equipment and instrumentation facilities, with expert operators;
- early exposure to newly developed characterization tools and methods;
- facilitated access to some large national facilities;
- a direct role in the training and development of graduate students, many of which are potential employees;
- participation in formulating research directions and proposals;
- joint publications and inventions;
- workshops and short courses, often formulated in concert with industrial partners;
- professional-development opportunities through visiting scientist "sabbatical" experiences at universities; and
- center-based education and human-resource programs that can provide access to underrepresented students.

Of course, it is important to recognize that the academic sector benefits enormously from industrial outreach as well. The introduction of valuable industrial perspectives—through industrial visiting scientists, participation of industrial members on advisory boards, co-advising of graduate students, and participation in topical workshops—introduces students and faculty to the issues and obstacles that confront industrial scientists in the "real world" of science and engineering. This environment naturally produces students and postdocs—the next generation of scientists and engineers—who are highly sought by industrial laboratories. Equally important is the advisory role that industrial partners play in the evolution of research at the centers. Company scientists and engineers often provide objective advice and act as unbiased sounding boards, substantially raising the quality and widening the impact of center research.

It is abundantly clear that MRSECs are playing an important role in fostering academic–industry connections, catalyzing research collaborations, and creating a synergism that, with proper direction, can only enhance the missions of both sectors. The success of industry outreach, however, relies on the willingness of both parties to recognize the differences in their cultures and missions—short-term needs versus long-term fundamental research, product commercialization versus student education—and individuals who will spend the considerable effort often required to ensure a successful collaboration.

How to Get Involved

This article has been an overview of the Materials Research Science and Engineering Center (MRSEC) program that is sponsored by the U.S. National Science Foundation. As can be seen by the examples given in this article, in the sidebar on shared experimental facilities (see p. 644), and the many more examples that can be accessed through the MRSEC Web site (www.mrsec.org), this group of centers provides a great resource that can be used by other technical institutions worldwide. Interested parties are encouraged to contact the centers that offer shared facilities or research programs



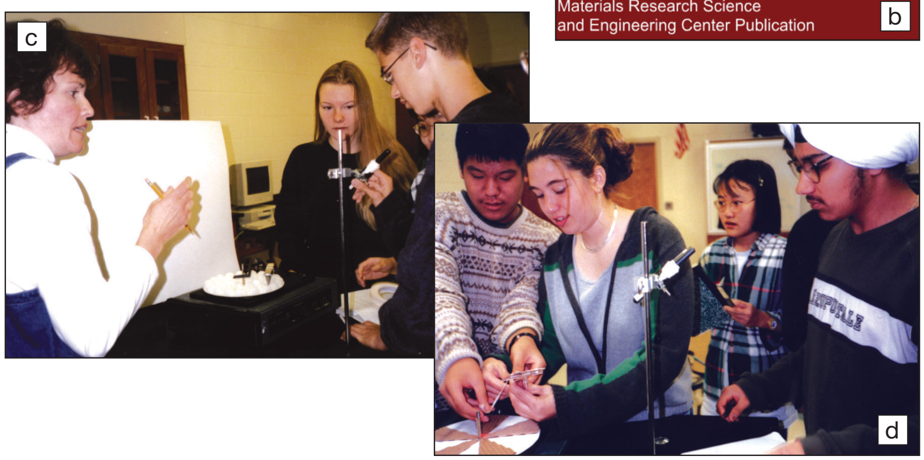
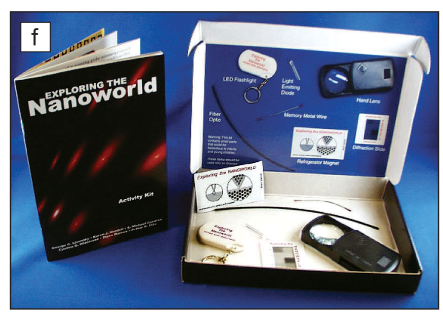


Figure 3. Educational activities are an integral component of each Materials Research Science and Engineering Center (MRSEC).

(a)–(b) The MRSEC Research Experience for Undergraduates (REU) program introduces undergraduate students to the field of materials science. (a) Nagalingam Balakrishnan (left), a professor of United Tribes Technical College, makes inverse opals with Anna Gopher (right), a student from the United Tribes Technical College, and Andreas Stein (center), a University of Minnesota MRSEC research faculty member. (b) The Inverse Opal Photonic Crystals Laboratory Guide *contains step-by-step procedures for the synthesis of crystals based on macroporous metal oxides. It is co-authored by Rick Schroden, a graduate student at the Minnesota MRSEC, and Balakrishnan. The guide is available for downloading on the University of Minnesota MRSEC Web site, www.mrsec.umn.edu/mrsec/main.shtml.*

(c)–(d) Princeton University Research Experience for Teachers (RET) participant Debbie Desser helps students make a "model" atomic force microscope using a turntable. (c) Desser (left) shows how to adjust the laser pen to make it reflect from the probe onto the white board. (d) Students attach the probe to the turntable arm. Currently, Desser is demonstrating at her school the use of an actual portable scanning tunneling microscope using a software program to study the atomic structure of graphite and gold samples.

(e) Héctor D. Abruña, a member of the Cornell Center for Materials Research, explores the nature of chemical reactions, using cornstarch and water, with children in the Esperanza program in Ithaca, New York. The Esperanza program focuses on Latino students in kindergarten through the 6th grade; lessons are conducted in Spanish.



(f) The "Exploring the Nanoworld" kit, developed by the MRSEC at the University of Wisconsin—Madison and based on a 32-page color activity booklet that places the nanoscale in context and includes a dozen experiments. The kit includes a light-emitting diode circuit, an optical giver, a shape-memory metal wire, a refrigerator magnet, a diffraction slide, and a 9-V battery. Kits are available through the Institute for Chemical Education (http://ice.chem.wisc.edu).

Shared Experimental Facilities

One of the missions of each Materials Research Science and Engineering Center (MRSEC) is to support shared experimental facilities that are properly staffed, equipped, and maintained. Naturally, the network of facilities boasts a wide range of processing tools, fabrication facilities, and materials characterization techniques. However, new trends in materials research have led to the creation of shared computational facilities as well as laboratories for molecular and biochemical studies. On average, the centers commit 16% of their budget for the shared experimental facilities. In many cases, the contribution from the MRSEC budget is only a fraction of the cost of maintaining and staffing a facility. By leveraging the MRSEC funds against those from other sources, state-of-the-art laboratories are provided that would not otherwise be possible.

These facilities are accessible not only to users from the center, but to users from other institutions and sectors. They also play important roles in many of the educational programs run by the centers, as typically more than 50% of the users are graduate students and approximately 10% are undergraduate students. The facilities are often used for demonstrations in the education programs. The balance of users is made up from other sectors including government and industry. This latter mix often provides the basis for collaborations that might not otherwise have occurred.

To illustrate the types of collaborations encouraged by the centers, here are a few of the numerous success stories:

- Researchers at Lucent Technologies collaborated with scientists in the Cornell University MRSEC to study transistor gate dielectrics. Using atomic-scale electron energy-loss spectroscopy in the ultrahigh-vacuum scanning transmission electron microscopy (UHV-STEM) facility, the researchers were able to demonstrate that the thinnest usable silicon dioxide gate dielectric is 0.7 nm, beyond which the material becomes conducting. This information is important because it places a fundamental lower limit on the size of silicon-based devices.
- A focused ion-beam (FIB) system maintained by the University of Virginia MRSEC is a hub of nanofabrication, materials characterization, and educational activities. Researchers at this MRSEC used their FIB system to create a three-dimensional image detailing the nanoscale chemistry and structure of a high-temperature Ni-Al alloy developed by the General Electric Company. This image is illustrated in Figure 4a. In addition, an undergraduate student, Brandi Tregre, working with faculty advisors James Groves and John Bean at this MRSEC, developed a computer visualization of the fundamental operating principles of these FIB systems that is being used to train future generations of students.
- In a multi-institutional collaboration among Sandia National Laboratories, Carnegie Mellon University, the Massachusetts Institute of Technology, and the National Institute of Standards and Technology, set up to study the microstructural origins of internal stresses in sintered alumina ceramics, researchers used microscopy resources available at the Carnegie Mellon MRSEC to generate input data needed for object-oriented simulations (see Figures 4b and 4c).
- As part of a collaboration between the Columbia University MRSEC and International Paper, undergraduate student Andrew Miller was able to analyze surface properties by photoelectron spectroscopy using the x-ray photoelectron spectrometer in the center's shared facilities (see Figure 4d).

Thus, these shared facilities not only further materials research in individual groups, but they also provide a strong catalyst for collaboration. Those interested in using such facilities are encouraged to examine the MRSEC Web site (www.mrsec.org) as well as the links listed there for the individual universities.

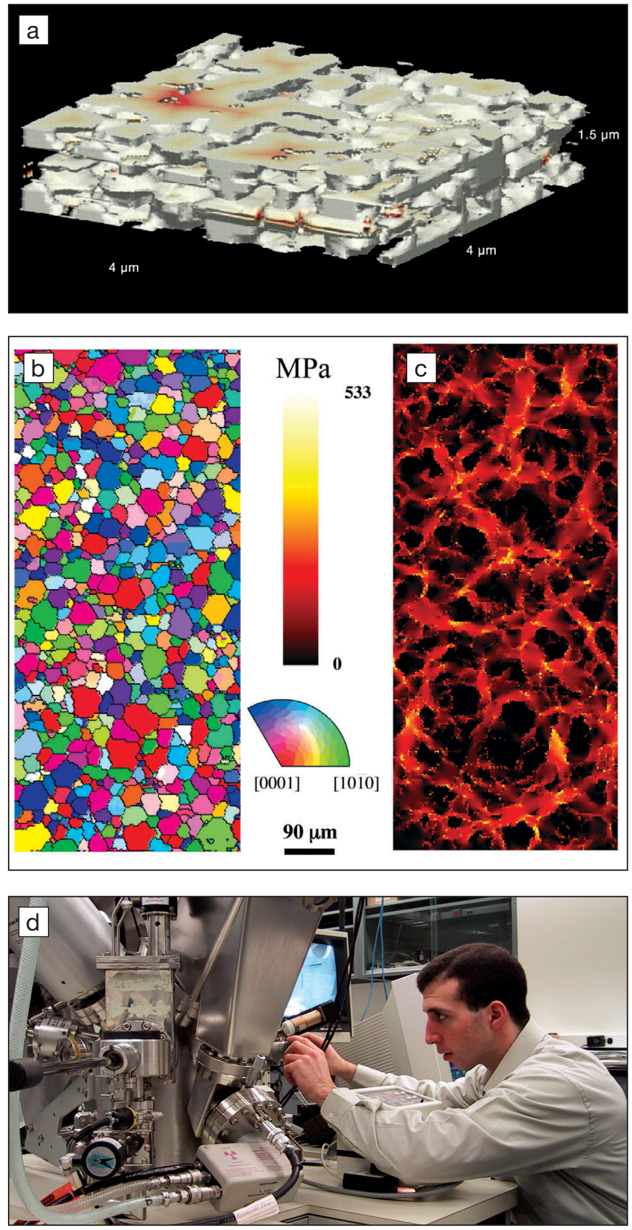


Figure 4. Materials Research Science and Engineering Centers (MRSECs) support shared experimental facilities in which different types of research collaborations occur. (a) Courtesy of the University of Virginia MRSEC: three-dimensional secondary-electron reconstruction of the nanostructure of the γ′ phase in a Ni-based superalloy. The spatial resolution of this technique is about 20 nm, and the reconstructed volume contains several million independently measured data points.

(b)–(c) Residual-stress distribution in sintered alumina after the temperature is decreased by 1500°C. (b) An orientation map of the microstructure, with the grain normals given by the colors in the stereographic triangle. (c) Calculated maximum principal stresses in the same area. Courtesy of the Carnegie Mellon University MRSEC.

(d) Columbia MRSEC undergraduate student Andrew Miller works with the x-ray photoelectron spectrometer in the Columbia University MRSEC shared experimental laboratory. Photo courtesy of J. Cross and I. Herman.

Table II: Representative Industries and National Laboratories Participating in MRSEC Research.

Companies	
Abbott Laboratories	LEGO Dacta
Advanced Surface Technology	Lincoln Labs
Advantica Stoner	Liquid Metal Corp.
Affymetrix	Lockheed Martin
Agilent	Lord Corporation
AKM	Lucent Technologies
Alcoa	LumiLeds/HP
Aldrich	Mechanical Resources
Allegheny Teledyne	Micro Precision Bearings
Allied Signal	Millipore
American Superconductors	Mitsubishi Research
AMGEN	Molecular Geodesics
Applied Materials	Motorola
Arryx, Inc.	MSI, Inc.
ATML	NEC
BASF	Nexia Biotechnology
BP-Amoco	Nippon Steel
Bayer	Northrup-Grumman
Candescent Technology Corp.	nPoint
Caterpillar	NVE, Inc.
Cheil Industries	Ontario Hydro
Clorox Technical Center	Osram Sylvania
Confluent Photonics	Pechiney (France)
Corning	Photonic Data Systems
Cortland Line	Polaroid
Crystal IS	Polysciences, Inc.
Delta F. Corp.	Praxair Spray Systems
Dow Chemical	Q-Sense
Dow Corning	Quantum Corporation
Draper Laboratory	Retlaw, Inc.
Dupont	Reveo, Inc.
Eagle Picher Technologies	Rhodia
Eastman Chemical	Rockwell-Boeing
Eastman Kodak	Rockwell Science Center
Electricited de France	Rohm and Haas
Elf-Atochem	Samsung
Englehard	Schenectady International
Epitaxx	Schlumberger Doll
Exxon Chemical	Sckisui Chemical Co., Ltd.
Exxon Mobil	Seagate Technology
FEI Company	Sensors Unlimited
Fina	Sermatech
Ford	Shipley Co.
GE	Siemans Westinghouse
Genpak	Southwest Research Institute
Genzyme	St. Gobain-Norton
Gillette	Sulzer-Metco
H.C. Starck	Surface Logix
Hercules	SYMYX Technologies
Hewlett-Packard Agilent	TotalFinaElf
Hilord Chemical	TSL
Hoechst-Celanese	U.S. Steel
Hyperion	Unilever PLC
IBM	Uniroyal
IGEN	United Technologies
Implant Sciences	Universal Display
IMRE	Westinghouse Bettis
Intelligent Fiber Optic Systems	Xerox
Johnson & Johnson	Xerox PARC
Kawasaki Steel	
National Laboratories	
Argonne	Naval Research Laboratory
Battelle Pacific Northwest	Oak Ridge
Brookhaven	Sandia
Lawrence Livermore Laboratories	National Research Council (Canada)
Los Alamos	Risoe (Denmark)
National Institute of Standards and Technology	

that could be of interest to them. In particular, the use of shared facilities often provides a way to stimulate research between different groups, since that use often brings researchers to the MRSEC sites. It is hoped that this article will serve as an introduction to these centers and will stimulate further collaboration.

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