Center for Materials Science and Engineering

The Materials Research Science and Engineering Center (MRSEC) at MIT, funded by the National Science Foundation (NSF), was established in 1994 as the core program of the Center for Materials Science and Engineering (CMSE). In November 2014, NSF awarded CMSE a renewed six-year $16.2 million MRSEC center grant to fund CMSE's research and educational outreach programs as well as its shared experimental facilities (SEFs) from November 2014 to October 2020. This award was the culmination of an extensive two-year internal and external review process and proposal preparation at CMSE headquarters that enabled CMSE to compete with over 150 other national institutions to win one of 12 NSF MRSEC center awards for this six-year period.

CMSE promotes and facilitates interdisciplinary research and education in the science and engineering of materials. MIT has an exceptionally strong and broad effort in materials science and engineering involving more than 200 faculty members in 13 different departments in the School of Engineering and the School of Science. CMSE plays the critical role of bringing this diverse materials community together by encouraging and supporting collaborative research and innovative educational outreach programs and by providing state-of-the-art shared experimental facilities (SEFs). The clear and important mission of CMSE is to enable—through interdisciplinary fundamental research, innovative educational outreach programs, and directed knowledge transfer—the development and understanding of new materials, structures, and theories that can impact the current and future needs of society. The complexities of such research clearly require input from industry and the expertise of many faculty members working collaboratively in a team-based approach.

The Center for Materials Science Engineering promotes collaborative research through several mechanisms: interdisciplinary research groups (IRGs), seed and initiative projects, SEFs, and outreach programs. While seed funding preference is given to young faculty, CMSE uses seed and initiative funds to support research that has the potential of redefining the direction of an existing IRG or leading to the creation of a completely new IRG. Seed funding provides CMSE with the flexibility necessary to initiate high-risk, transformative research. Our research programs typically support a total of 30 to 40 faculty members from 10 or more departments. During the period of our 2008–2014 MRSEC award, researchers published results in over 500 papers and were awarded 52 patents related to their MRSEC research, with 82 more patents issued or pending.

Our SEFs are used by numerous research groups from MIT as well as by outside academic and industrial communities. During the year ending February 16, 2016, 1,356 people used our SEFs, including 803 students and postdocs of MIT faculty in 24 academic departments, labs, and centers; 33 students and staff of faculty from 14 outside academic/research institutions; 180 students using the facilities for MIT lab subjects; and 19 staff of senior-level industrial managers.

Our educational outreach programs encompass a broad range of activities and age levels, with participation from K–12 students and teachers and undergraduates from other institutions. During the summer of 2015, 90 people participated in our various

core programs with support from CMSE-funded faculty, graduate students, and postdocs. CMSE MRSEC faculty also devoted many hours to tutoring students, making presentations to students and teachers, supervising high school students in their labs, and hosting groups of students visiting CMSE labs.

Interdisciplinary Research Programs and Scientific Accomplishments

During the 2015–2016 academic year, CMSE supported three IRGs, one super seed, and four seeds. The MRSEC grant supports 28 faculty from nine MIT departments and, through a subaward, one faculty member from the University of Central Florida. Selected research highlights from FY2016 are reported below.

IRG-I: Harnessing In-Fiber Fluid Instabilities for Scalable and Universal Multidimensional Nanosphere Design, Manufacturing, and Applications

This IRG explores fundamental issues associated with multi-material in-fiber fluid instabilities and uses the resultant knowledge to develop a new material-agnostic fabrication approach for the creation of nanoparticles of arbitrary size, geometry, and composition. This research sets the stage for discoveries, both fundamental and applied, in areas ranging from novel neuronal interface devices to delivery vehicles for pharmaceuticals, and potentially in the chemical and electronics industries.

IRG-I research is directed at the development of unique, multi-component nano-structured fibers and nanoparticles through the use of a newly discovered processing paradigm involving nonlinear fiber fluid instabilities. Members of this group have now fabricated and characterized, for the first time, a self-assembled, electrically contacted, and entirely packaged functional photodetecting fiber device system. Taking advantage of a new instability mechanism that kinetically targets a semiconducting domain while keeping adjacent conductor domains continuous, they were able to create approximately 10^5 self-assembled, discrete spherical devices per meter of fiber. New simulation results of the capillary breakup process provide a better match to experimental observations than does the previously developed numerical model. In a surprising development, the group, utilizing a new approach based on a mechanical-geometric instability associated with neck propagation, has also demonstrated the ability to create uniformly sized rods along meters of fiber. This approach can be used to create rods of a wide range of materials including silicon, germanium, gold, various glasses, silk, polymers, and even ice.

In pursuit of topographically defined fibers with applications in neuroscience, new fiber scaffolds with cylindrical and rectangular core geometries have been fabricated. It is known that microscale topographic features can accelerate nerve growth in vitro. To date, however, synthetic nerve guidance scaffolds have been largely limited to simple cylindrical geometries. IRG-I researchers have found that, independent of device size, grooved scaffolds yield more robust neurite outgrowth than rectangular or cylindrical scaffolds. The regenerative capacity of these scaffold cores was studied in vitro using dorsal root ganglia from neonatal rats in two clinical scenarios: limb loss and nerve injury. The ultimate goal of this work is the creation of fiber scaffolds capable of optomechanical guidance of nerve regeneration.

The IRG-I group has put forth a fundamentally new approach for using light to control the motion of nanoscale and microscale particles and objects. Overcoming the light-scattering limitations of current technologies, this new approach relies on a bidirectional, light-induced thermophoresis process. Computations using a new type of asymmetric nanoparticle that consists of two material faces show that the particles preferentially absorb light of different wavelengths regardless of particle orientation, thus allowing for bidirectional motion. Since this approach is insensitive to scattering and applicable to many particles at once, as well as particles that cannot be optically resolved, it may enable useful applications in biology, microfluidics, in vivo tasks, and colloidal science.

IRG-I is establishing a wide-ranging, materials-agnostic fiber fabrication approach that can be used to create complex, multi-component fibers with optical and electrical properties that allow development of unique fiber-based devices such as solar fabrics. The electronic and optical capabilities of these fibers can also be exploited as devices for stimulating and recording neuronal activity in humans to aid in the treatment of neurological disorders such as Parkinson's disease. The complex nanoparticles created in these fibers can be harvested for numerous other optical applications as well. On the fundamental side, this research offers a new paradigm for fluid-dynamic studies through the use of highly controlled environments for the observation of fluid instabilities involving multiple fluids co-flowing in hitherto unobtainable geometries and scales.

Faculty participants and department affiliations: Y. Fink, co-leader (Materials Science and Engineering [DMSE]); M. Soljacic, co-leader (Physics); J. Joannopoulos (Physics); S. Johnson (Mathematics); A. Abouraddy (University of Central Florida); and P. Anikeeva (DMSE).

IRG-II: Simple Engineered Biological Motifs for Complex Hydrogel Function

This IRG seeks to understand the fundamental biology, chemistry and materials science underlying the unique properties of biological hydrogels, and use this knowledge to design and create synthetic mimics that have the potential to revolutionize the design of water purification technologies and a range of biomedical applications.

IRG-II research seeks to understand the molecular mechanisms that govern the unique structure/property combinations of complex biological hydrogels and use this knowledge to create synthetic mimics with similar extraordinary properties. Using molecules engineered to mimic the peptide sequences found in nucleoporins, it has been found that the specific positioning of charged moieties with regard to hydrophobic domains can critically influence a wide range of hydrogel properties. The net result is the ability to dramatically modify mechanical properties and phase behavior by simply repositioning the charges within repeat units. By using proteinaceous fibers found in biofilms called curli fibers, this group has also incorporated nucleoporin-like peptides onto a curli scaffold with the goal of yielding living materials with selective and controllable permeability.

To better characterize the rheological properties of gel systems, this IRG has developed a particle tracking micro-rheology setup with temperature control in the 20–60°C range

that requires only a small amount of sample. IRG-II researchers have also reported on the synthesis of a new class of smart polymer materials with controllable network junctions through use of bio-inspired metal-coordinating polymers capable of self-assembly into and onto nanostructures with tunable properties. New results using four differently engineered crosslink structures suggest that it is possible to systematically control gel energy dissipation. These new results also provide insights into the mechanisms underlying the gel energy dissipation behavior of these materials.

In order to mimic the behavior of cartilage, IRG-II has further developed new experimental and theoretical methodologies to quantify the transport and rheological properties of glycosylated matrices and gels. To quantify chemical transport and rheological kinetics and to assess whether cationic peptides always bind to glycan matrices, techniques have been developed to measure transport of charged peptides into and across glycan gels via fluorescently tagged peptides and real-time spectrofluorometry. Changes in mechanical swelling and swelling pressure, for example, were explored by diffusing the highly cationic protein avidin into the heavily glycosylated matrix of cartilage. When avidin diffuses into the matrix, mechanical stress relaxation occurs as a result of shielding of electrostatic interactions between matrix glycans.

The fundamental knowledge and new materials developed within this IRG will lead to next-generation materials with potentially wide engineering implications, such as the design of self-healing filtration systems for water and food purification, new antimicrobial coatings for implants, or cartilage substitutes with high durability and lubrication capacity. New insights into the origin of the extraordinary properties of biological hydrogels are also expected with an understanding of the interplay among three common motifs found in these materials: repeat domains, reversible crosslinking, and glycosylation.

Faculty participants and department affiliations: K. Ribbeck, co-leader (Biological Engineering); P. Doyle, co-leader (Chemical Engineering); B. Olsen (Chemical Engineering); N. Holten-Andersen (DMSE); J. Johnson (Chemistry); A. Grodzinsky (Biological Engineering, Electrical Engineering and Computer Science [EECS], and Mechanical Engineering); P. Hammond (Chemical Engineering); and T. Lu (EECS and Biological Engineering).

IRG-III: Nanoionics at the Interface: Charge, Phonon, and Spin Transport

This IRG seeks to discover the coupling mechanisms between oxygen defects and the transport of phonons, spin, and charge at the interfaces of complex oxides. The resultant knowledge will guide the design of materials for the next generation of miniaturized and high-efficiency devices for energy conversion and for information processing and storage.

Utilizing density functional theory (DFT) simulations and a modern theory of polarization, IRG-III researchers have uncovered a non-negligible polarization on neutral oxygen vacancies in $SrTiO_3$. This is important, as the effects of field-induced polarization on charged defect equilibria in semiconducting oxides are largely unexplored and are believed to be important in applications such as memristors,

fuel cells, and solid-state batteries. In addition, a pressure-temperature dominance diagram was computed for electron defects in $SrTiO_3$ using DFT and quasi-harmonic approximation for free energies. Tensile hydrostatic stress was found to stabilize small polarons even at low temperatures, indicating one way that strain can couple to electronic states, conductivity, and reactivity in these materials.

IRG-III researchers have used an electrical bias in conjunction with in situ X-ray diffraction to demonstrate fast and reversible switching between different phases of strontium cobaltites ($SrCoO_x$). Topotactic phase transitions of functional oxides induced by changes in oxygen non-stoichiometry can alter multiple physical and chemical properties, including electrical conductivity, thermal conductivity, magnetic state, oxygen diffusivity, and electrocatalytic reactivity. Reversible control over these phase transitions is thus of great interest. Time domain thermoreflectance measurements were used to study the coupling of ionic defects with phonons in $SrCoO_x$. As a result of this ion-phonon coupling, and by controlling oxygen ion content and migration by electric fields, thermal conductivity was found to increase with increasing applied electrical fields. This effect was attributed to a change in structure from Brownmillerite to Perovskite at sufficiently high electrical fields that change the oxygen content, x, in $SrCoO_x$. In related materials, DFT calculations have revealed that the origins of magnetism and ferroelectricity in multiferroic oxide thin films are related to the interplay among oxygen vacancies, B-site ions, and structural distortions of the material, suggesting a route to multiferroicity in this class of oxides.

Voltage-controlled formation of oxygen vacancies and their effects on magnetism at ferromagnetic metal/metal-oxide interfaces have been studied in Co/GdO_x thin-film stacks. A Co/GdO_x/Au stack was found to behave as a metal-air nanobattery whose charge state controls the magnetic properties of the Co. Results demonstrate that the oxygen vacancy concentration at the Co/GdO_x interface can be modulated by a gate voltage that, in turn, can be used to modulate the magnetic properties. Moreover, a built-in voltage established in the device can be used to switch interface anisotropy, permitting zero-external-bias magneto-electric switching in a thin-film ferromagnet.

The research of this IRG has transformative implications for energy and information technologies. By providing a better understanding of the central role that oxygen defects play in the electrical, optical, and magnetic properties of metal oxides at interfaces, this effort is expected to influence the next generation of emerging devices such as nanoionic and thermoelectric devices, fuel cells, and memristive and magneto-electronic devices.

Faculty participants and department affiliations: C. Ross, co-leader (DMSE); B. Yildiz, co-leader (Nuclear Science and Engineering); G. Beach (DMSE); G. Chen (Mechanical Engineering); H. Tuller (DMSE); and K. Van Vliet (DMSE and Biological Engineering).

FY2016 Super Seed Research: Magnetically and Optically Driven Topological Semimetals

The goal of this research project is to discover new topological semimetals (TSMs). TSMs are analogous to topological insulators but occur in non-insulating band structures; they have conduction and valence band crossings at so-called Dirac or Weyl points that are protected

by symmetry. TSMs have been predicted to have a range of exotic properties that make them exciting targets for study. This project focuses on two specific directions to explore new TSMs. The first direction focuses on TSMs driven by magnetic order. Thus far TSMs driven by crystal symmetry breakings have been reported, but those driven by breaking time reversal symmetry (magnetism) have not. Coupling to magnetic order would offer unique controllability and chiral electronic behavior of great interest. The second direction is the investigation of photo-driven TSMs termed Floquet topological semimetals (FTSs). This leverages the ability to dress conventional Bloch states by intense laser light to form new band crossings. This super seed's main research accomplishment thus far has been the synthesis and initial study of a Dirac semimetal candidate and FTS candidate $ZrTe_5$. For three-dimensional crystals, this system is predicted to be at the boundary between topologically distinct weak TI and strong TI phases. The transition point between these two phases represents a Dirac semimetal. For the study of FTSs, it is important to find a system positioned near such a transition so that the application of laser light can form new band crossings.

Faculty participants and department affiliations: Joseph Checkelsky (Physics), Liang Fu (Physics), and Nuh Gedik (Physics).

FY2016 Seed Research

- Seed 1: Chemically Modified Carbon Cathodes for High Capacity Li-O_2 Batteries (Yogesh Surendranath, Chemistry). This seed seeks to improve the long-term performance of Li-O_2 batteries by developing electrode surface treatments that inhibit the growth of insoluble Li_2O_2 precipitates.
- Seed 2: Interface Engineering of Silicon-Oxide Core-Shell Nanorods for High-Efficiency Water Splitting Photocatalysts (Alexie M. Kolpak, Mechanical Engineering). This seed utilizes computational methodologies to explore and optimize the photocatalytic water splitting properties of Si-TiO2 core-shell nanorods in solar energy conversion schemes.
- Seed 3: Single Crystal Study of Electronic Topology and Correlation (Joe Checkelsky, Physics). This seed seeks to grow single crystals of topological materials with significant electronic correlation to explore new states of matter with novel magnetic and transport properties.
- Seed 4: Direct Deposition of Catalysts on Porous Metallic Foams for Efficient CO2 Electroreduction (Fikile R. Brushett, Chemical Engineering). This seed seeks to develop microporous metal foam electrodes with nanostructured electrocatalysts for use in high-performance CO2 conversion devices.

Shared Experimental Facilities

Our SEFs are a critically important resource to our MRSEC program and to the MIT community, as well as a number of outside academic and industrial organizations. Currently we run four major facilities, Materials Analysis, Electron Microscopy, X-ray Diffraction, and Nano Materials, staffed by a team of highly motivated professionals. During the year ending February 2016, 1,035 different individuals utilized our facilities.

Beyond the special role our SEFs play in the training and education of MIT students, they are also an important part of CMSE's education programs. Undergraduates participating in the summer internship programs (Research Experiences for Undergraduates [REU] and Community College Students) are trained to use equipment in the SEFs to conduct their research. Teachers in the Materials Research Experience for Teachers (MRET) program spend one morning each week learning about the capabilities and research applications of the equipment in the SEFs. Some of them are also trained to use the instruments for their research projects. Finally, the SEFs are included in visits to CMSE by various groups of middle and high school students.

SEF staff members play an important part in many of our educational outreach programs and enthusiastically embrace this role. For example, they train MIT graduate and undergraduate students as well as our summer educational outreach participants. During this academic year, about 180 undergraduate students used the facilities as part of their laboratory subjects.

In addition, SEF staff members offered a number of mini-courses during MIT's 2016 Independent Activities Period to train students to operate SEF equipment and apply the latest techniques to their research problems. In January of 2016, a total of seven courses were offered to the MIT community.

Materials Research Facilities Network

During FY2016, students and faculty from around the United States and the world came to MIT through an NSF Materials Research Facilities Network (MRFN) funding component of our MRSEC grant. This funding allows students and faculty who do not have access to instruments such as those in our SEFs to visit MIT and learn how to use these types of instruments. A process has been established that involves the submission of a short proposal outlining the work to be done and how the results will impact the proposer's research program and, if relevant, educational activities. Groups typically stay from Sunday evening to Saturday morning, and SEF managers set aside blocks of time for training and assisting with running samples and training students. All participants register in the Coral lab management system and take the required safety courses to enter the facilities.

During the summer of 2015, Dr. Eugenia Ciocan of Bunker Hill Community College, a participant in the 2015 MRET program in Professor Polina Anikeeva's lab, used MRFN funding to complete her research in the CMSE electron microscopy and X-ray facilities. Also, Professor Maria Beppu (State University of Campinas, São Paulo, Brazil) sent a student to continue research in the analytical facility during October 2015, and Professor Maria Del C. Cotto Maldonado (Universidad del Turabo, Puerto Rico) sent a student to work in our SEFs in early November 2015.

Collaborations, Outreach, and Knowledge Transfer

Our MRSEC-supported faculty has ongoing collaborations with numerous industrial partners that range from the funding of applied projects (often based on fundamental work carried out within the center) to the development of new technologies and products. We work closely and effectively with MIT programs and centers such as the

Materials Processing Center (MPC) and the Industrial Liaison Program (ILP), which connects MIT research to industry. These organizations combined have more than 200 member companies. During this reporting period, MRSEC faculty and/or their group members engaged in nearly 50 meetings with representatives from a broad range of domestic and foreign companies, including visits from industrial representatives, faculty visits to different firms, briefings to company executives, and teleconferences. A partial list of these companies includes BP, the China National Offshore Oil Corporation, Jaguar Land Rover Limited, the KAO Corporation, Medtronic Inc., Nippon Kayaku, the Northrop Grumman Corporation, Qualcomm Inc., Samsung Electronics, Shell, and Stanley Black & Decker. The CMSE director gave presentations about MRSEC to Haitian Plastic Machinery, the Saudi Basic Industries Corporation, the Tosoh Corporation, and the Wuxi Municipal Government.

MRSEC-supported faculty presented an overview of their CMSE research in two ILP-sponsored conferences: the 2015 MIT Research and Development Conference (Y. Fink and K. Van Vliet) and the 2016 MIT Japan Conference in Tokyo (K. Van Vliet). The Research and Development Conference was attended by more than 400 representatives from companies including 3M, Accenture, the Campbell Soup Company, ExxonMobil, GE, Lockheed Martin, Merck, Nestle, Novartis, Procter & Gamble, Raytheon, Samsung, Siemens, Volvo, and Yamaha. The MIT Japan Conference, attended by 265 researchers from industry, highlighted advances in key areas such as advanced materials, electronics, information technology, neuroscience, chemical engineering, and food technology. A partial list of the 50 companies represented at the conference includes Astellas Pharma, Fujitsu, Honda, LG Holdings, Merck, Mitsubishi, Nippon Kayaku, the Toshiba Corporation, and Yamaha.

In May, CMSE director Michael Rubner was the keynote speaker at the 2016 New Frontier Symposium at the 10th World Biomaterials Congress in Montreal, Canada. At the event, Rubner presented his CMSE-supported research “Cellular Backpacks for Biomedical Applications.” This six-day symposium, attended by thousands of biomaterials professionals from more than 60 countries, included workshops, poster sessions, technical forums, roundtable discussions, and lectures.

In October 2015, CMSE contributed to the showcase MIT materials event, the annual Materials Day at MIT program organized by MPC. Co-organizing the event’s poster session allows CMSE to highlight MRSEC-funded research and connect this research directly to managers and researchers from industry and government laboratories. All MRSEC-supported researchers are encouraged to have their group members contribute posters to this event. The title of this year’s Materials Day was “Quantum Materials.” About 225 registered guests attended the meeting, coming from industry, government laboratories, hospitals, MIT, and other universities. In addition, researchers and students from MIT joined the event throughout the day on a walk-in basis. Representatives from more than 50 US and foreign companies, laboratories, and universities attended the event, including employees of General Motors, LG Electronics, Lockheed Martin, Procter & Gamble, Raytheon, Samsung Research America, Suncor Energy, and the US Army Research Laboratory. The capstone poster event included posters from CMSE students and others from the MIT materials science community. This year, out of nearly

60 posters submitted, 22 originated from students and postdocs of faculty supported by CMSE funding. Half of the CMSE submissions were from students and postdocs supported by the current MRSEC award, while the other half were from faculty involved in the former MRSEC award, whose research under that award continues to generate productivity. The poster session was judged by a panel of members from MPC's advisory board, which includes research managers from industry.

Another important mechanism for knowledge transfer is the creation of new companies and businesses (and related jobs). Currently active CMSE-related companies that were started by MRSEC faculty, students, or postdocs include OmniGuide Inc., LumArray, Luminus Devices Inc., QD Vision, Kateeva, and WiTricity Corporation. These various companies were founded to develop novel devices and components based on discoveries made within the MRSEC program and funded, in several cases, exclusively through NSF. Additionally, Nanosys and Quantum Dot Corporation (bought by Invitrogen) are companies whose technology platform is based in part on CMSE-supported fundamental research. It is estimated that total direct job creation by the most closely CMSE-related companies (OmniGuide, LumArray, Luminus Devices, QD Vision, Kateeva, and WiTricity) is about 400 jobs and growing.

MIT's Technology Licensing Office is kept aware of new discoveries emanating from CMSE research and helps researchers file patents and issue licenses. Since the beginning of our new MRSEC grant in November 2014, nine new patents related to MRSEC have been issued, and 11 new patent applications/provisional patents are pending.

The center's MRSEC-supported faculty enjoy a high level of outside collaboration. During the period from August 2015 through February 2016, there were 37 collaborations (27 of which were international); these include one industrial collaboration, 32 collaborations with outside academic researchers, and four collaborations with government laboratories and agencies (all MRSEC related). In addition, a number of CMSE faculty members supervised students in departmental co-op programs that carry out research projects in a wide variety of industrial laboratories.

Education and Human Resources

CMSE has worked hard to establish a wide-reaching and diverse portfolio of educational outreach programs that are both innovative in nature and responsive to the needs of educators and students. We have now put in place a broad range of well-received programs for high school students and teachers as well as for undergraduate and graduate students. Our programs are managed by a full-time education officer who works closely with a faculty education program leader, the center director, and the assistant director.

In addition to involvement in CMSE's formal education activities (outlined below), MRSEC-supported faculty, research scientists, and graduate students participate in outreach activities with local schools, religious communities, and professional organizations.

For the past 11 years, CMSE has collaborated with Roxbury Community College (RCC) and Bunker Hill Community College (BHCC), two minority-rich two-year colleges in Boston, to make research experiences available to their students. The objective of this dedicated REU program is to engage community college students in current materials research and encourage them to pursue careers in science and engineering.

Precollege Education

Materials Research Experience for Teachers

For the past 17 years, CMSE has operated a successful MRET program. This program brings high school and middle school teachers to MIT to participate in CMSE research. The teachers spend seven weeks immersed in research during the first year of the program and then are invited to return the following summer for a flexible period of time devoted to the development of material that will transfer their research experience to their classroom teaching. The major components of the program are research, weekly discussion meetings, SEF tours, and the development of classroom materials. An important goal of the program is to document the materials developed by the teachers so that they can be shared with other educators. Lesson plans written by the teachers are distributed to other science teachers and used in teacher workshops.

Relationships between CMSE and the MRET participants extend beyond the summer program. Over the years, these continued collaborations have permitted class visits to MIT, K–12 school presentations by MRSEC researchers, and student involvement in research. In December 2015, MRET participant Paul Kasili brought 12 students from his two community college biology classes to visit the CMSE X-ray SEF. One of the program's 2015 participants, Sean Müller, has worked with CMSE for a number of years developing lab projects that are used in his high school classroom as well as in one of MIT's freshman seminars.

Feedback from recent participants in the MRET program indicates that they were satisfied with the program and that it has had a meaningful impact on their teaching. The most frequently cited enhancement of their classroom teaching as a result of their research experience at CMSE is the incorporation of more hands-on lab projects. The program participants often share their units and MRET experience with fellow teachers at their schools and at regional and national meetings.

Science Teacher Enrichment Program and Women's Technology Program

CMSE offered its Science Teacher Enrichment Program (STEP) for the 14th time in the summer of 2015. STEP consists of a one-week workshop, "Dustbusting by Design," that focuses on increasing middle and high school teachers' content knowledge and providing them with experience in engineering design. The workshop correlates with the Massachusetts state science learning standards. Participants spent the first four days of the program in a machine shop on campus learning about the design challenges associated with the motor in a hand-held vacuum and then immersed themselves in the engineering design process as they constructed motors of their own design. The final half-day consisted of a seminar on teaching the design process in K–12 classrooms. The

lab portion of the program was simultaneously taught to 40 high school girls in the Women's Technology Program.

Participants in STEP receive a small stipend and professional development points. They are recruited from local school districts, from former applicants to the MRET program, and through other MIT-based programs for educators. Two teachers participated in the 2015 STEP. Entrance and exit surveys were used to determine how well the workshop met the teachers' professional needs. Both teachers indicated that the program more than met their expectations and provided them with material they intend to use with their students. On the survey, one teacher wrote, "This was a great experience. The lab staff were magnificent, the professor inspiring, the opportunity to observe the learning process with high school students very fruitful for a practicing teacher. I was looking for a novel engineering professional development [program] and I got it and then some!"

A companion effort to STEP is CMSE's collaboration in the Women's Technology Program (WTP) in EECS. In this four-week summer residential program, 40 high school girls from across the country take classes in math, computer science, and engineering. The program is designed to address a gender imbalance in the field of engineering by increasing the girls' interest and confidence in pursuing engineering careers. CMSE invites the WTP participants to join the lab portion of STEP to gain hands-on engineering experience. For the past 13 years, this has been an extremely successful collaboration. WTP alumni report that this motor-building lab is an exciting part of the program. In 2015, CMSE supported WTP by providing the curriculum and supplies for this part of the program, and we will continue to do so in 2016.

Workshops and Public Events

MRSEC faculty and students contributed content to programs on campus and at local public events. In January 2016, Professor Steven Leeb conducted two energy-themed workshops, one attended by 28 graduate-level participants on the MIT campus and the other attended by 50 graduate-level participants in Abu Dhabi, United Arab Emirates. In both workshops, participants engaged in a "Drivebot" assembly, which provides students with the opportunity to assemble their own robots from scratch, beginning with the mechanical and electromechanical drive components. Professor Patrick Doyle visited Nixon Elementary School in Sudbury, MA, to give 20 students a hands-on demonstration on gelling systems. Professor Alan Grodzinsky hosted a high school student who visited his lab on the MIT campus to learn about research in biomaterials and gels. Professor Yogesh Surrendranath visited East Boston High School to teach students how to build electrolyzers and how to create and characterize a water-splitting catalyst. Also, in January 2016, Professor Harry Tuller launched "Introduction to Green Technology," a course he co-founded and collaborates in teaching to a group of 15 to 20 visiting students from local high schools selected according to their level of motivation and interest in clean energy. Special care was taken in the search for students to encourage a larger pool of interest from female and minority participants. The group will continue to meet on the MIT campus on a biweekly basis for eight 2.5-hour sessions composed of lectures and group discussions.

Science and Engineering Program for Middle School Students

The center has operated a science and engineering program for seventh- and eighth-grade students from two Cambridge public schools for the past 24 summers. The objectives of the program are to introduce students to the field of materials science and engineering, demonstrate that science and engineering can be fun, and provide students with an opportunity to experience a college environment. The program consists of a full summer week of hands-on and inquiry-based science and engineering classes for students from each school. During the summer of 2015, 13 seventh- and eighth-grade students attended with their science teachers. Seven of them were girls and four were members of underrepresented minority groups.

The students participated in hands-on activities presented by faculty, staff, graduate students, and undergraduates. The 2015 program included classes on ultraviolet light, simple DC motors, electric circuitry, polymers, glass blowing, metal casting, sensors, and solar cells. In addition, a group of graduate students presented table-top demonstrations of energy projects related to their research. Participants also toured the MIT Museum and Wright Brothers Wind Tunnel. In review discussions at the end of each week, the students were able to describe the material presented and explain what they saw. An indication that the program met the goal of demonstrating that science and engineering are fun is that all of the students who completed exit surveys responded that they would recommend the program to their friends.

Undergraduate Education

Undergraduate Research Opportunities Program

The center provides opportunities for MIT undergraduates to participate in MRSEC research through MIT's Undergraduate Research Opportunities Program (UROP). Participants in this program work on MRSEC research on a part-time basis during the academic year and full time during the summer. MRSEC typically supports three students each academic term and three during the summer. UROP students sometimes continue their research beyond one term. Also, MIT provides funding for a limited number of UROP participants, some of whom work on MRSEC research. During this reporting period, MRSEC directly supported five undergraduates, two of whom were women. CMSE faculty report that an additional 15 students (including 10 women and one minority student) working on their MRSEC research were supported by MIT directly or worked for academic credit.

Summer Research Internship Program

In collaboration with MPC, CMSE sponsors the Summer Research Internship Program (through the NSF REU program). The program's major goals are to provide undergraduates from other institutions an opportunity to perform cutting-edge materials research and to attract students to graduate studies in materials science and engineering. The two centers intend to continue this collaboration. The program is open to US citizens and permanent residents who will be juniors or seniors the following fall. We received 180 applications for the summer of 2015, which were reviewed by a committee consisting of the CMSE director and staff from both centers. Participants were chosen from this pool on the basis of academic performance, interest statements, and

faculty references. The 12 students accepted into the program for the summer of 2015 included six women and five students from underrepresented minority groups. Because the CMSE/MPC program is well established as a quality internship program on campus, other organizational units seek to fold their summer undergraduate researchers into the program. Last summer, the stipends of two students in the REU program were paid through an Energy Frontier Research Center funded by the US Department of Energy's Office of Basic Energy Sciences. These two students were selected from the pool of applicants to the REU program and participated fully in the program.

The nine-week summer internship program begins with a three-day symposium during which faculty present their research, describing the projects available for the interns. At the end of the three days, the interns select their projects for the summer. Throughout the summer, the interns, along with the REU students, participate in weekly mentoring meetings and seminars. They also present posters at the MRET/REU poster event.

Diversity Enhancement Activities

CMSE has a history of promoting and encouraging traditionally underrepresented minority groups and women to participate in materials research. This is accomplished through educational outreach efforts, special programs for graduate research assistants, and efforts to coordinate activities with faculty, postdoctoral associates, and graduate and undergraduate students. A few of these activities are summarized below.

Community College Program

CMSE's Community College Program (CCP) is another targeted REU program designed to enhance the diversity of undergraduate participants in MRSEC's research and education programs and to broaden participation among science and engineering professionals. CMSE partners with RCC and BHCC to provide their students with research opportunities and encourage them to pursue careers in science, engineering, and technology. CCP participants are selected by science faculty at their home institutions. Selection criteria include the students' academic background, statements of interest, and faculty references. A total of six students participated in 2015, three of whom were female and one of whom was a minority student. CCP students spent nine weeks on campus conducting research in faculty-led groups and joined the other REU students for weekly meetings and seminars. These meetings featured research discussions and speakers on intellectual property, graduate school admissions, poster preparation, and hot topics in materials science and engineering. CCP participants presented their research at the MRET/REU poster session.

Typically, community college students do not have opportunities to gain research experience at their home institutions. By participating in CCP, they learn research and technical lab skills that increase their confidence and prepare them to pursue bachelor's degrees and science and engineering careers. The MRSEC director and education officer meet separately with the CCP students as a group at least twice each summer to discuss their research and their career plans. In these meetings students have reported that, in addition to enhancing their research skills, their experience at MIT broadens their knowledge of possible science and engineering careers and provides a realistic picture of graduate work. Since the program's beginning, 32 (59%) of the participants have

transferred to or enrolled in four-year colleges. Of those, four have enrolled in graduate programs; three are currently pursuing graduate degrees in science and engineering, and another is earning an MBA. An additional student went on to medical school. Six CCP participants proceeded directly from community college to employment. Nine students continue at community college, and the status of seven other participants is unknown.

MRSEC collaborates with Professor Polina Anikeeva to broaden the impact of its partnership with RCC and BHCC. With CMSE support and her NSF CAREER grant funds, she embarked on a multiyear plan to engage BHCC and RCC faculty and students in her lab's research, thus extending MRSEC's outreach to a wider group of community college students and faculty. Two professors and two students from these institutions spent the summer of 2015 doing research with Professor Anikeeva's group as participants in CMSE's CCP and MRET programs. The intention is for the RCC and BHCC faculty to integrate their research experience into their classroom teaching. CMSE provided the professors' and students' stipends.

Partnership with Universidad Metropolitana

In 2008, MRSEC formed a collaboration with Dr. Juan Arratia at the Universidad Metropolitana (UMET) to enhance the research experiences of students at the three Puerto Rican universities affiliated with the Ana G. Mendez University System (UMET, Universidad del Turabo, and Universidad del Este). Dr. Arratia refers students to the CMSE/MPC Summer Research Internship Program. At least two intern positions a year are set aside for these students. A goal of the partnership is to recruit and retain Puerto Rican science, technology, and engineering graduates. Since its inception, 17 students have participated in the program, and an additional two students spent two weeks at CMSE working with graduate students to learn to use research instruments in the SEFs. Of the 19 students who have been involved in the program, four are still completing their undergraduate studies. Another five have proceeded to graduate school, one of whom has completed her PhD. Six others have completed their bachelor's degrees and are employed: three as engineers, one as a financial consultant, one in manufacturing, and one as a systems analyst. The career status of the remaining students is unknown. In addition to their research at MIT, undergraduates who participate in the REU program contribute to UMET's outreach to high school students in the San Juan area.

Enhancing Diversity within Existing Programs

Recognizing the importance of diversity in the pipeline of future scientists and engineers, CMSE seeks to impact the classroom experience of minority students by strengthening the materials content knowledge of their science teachers. CMSE is committed to achieving approximately 50% participation by teachers from schools with significant enrollments (above 50%) of underrepresented students. Three of the five participants in the 2015 MRET program taught at institutions that meet this requirement. In addition, CMSE directly engages local middle school students through its Science and Engineering Program for Middle School Students. Students who participated in this program in 2015 were drawn from the Putnam Avenue Upper School, where approximately 57% of the registered students are from underrepresented groups.

Postdoctoral Mentoring

CMSE has developed a robust postdoctoral professional development program. Over the past year, 17 postdoctoral associates worked on MRSEC research, 15 of whom were paid directly by the center. CMSE launched its postdoc mentoring program in 2010 with a director-led meeting of CMSE postdocs to identify their professional development needs and topics they would like to see addressed. As a result, a postdoc advisory committee was formed to provide input to the director about activities and services that would be beneficial to professional development. In 2011, with input from this committee, CMSE inaugurated a seminar series that features annual professional development events jointly sponsored by CMSE and a partnering MIT academic department. All postdocs working with CMSE faculty are invited to participate in the seminars, whether or not they are supported by MRSEC. The initial seminar, held in January 2011 and co-hosted by DMSE, featured a panel discussion focusing on career paths and balancing professional and family lives. CMSE partnered with the Department of Chemical Engineering to present the second seminar in 2012. At this event, a panel of faculty presented advice on finding and securing faculty positions, including information on the search process, interviewing, and negotiating a start-up package. A total of 75 postdocs attended these two events. On exit surveys, attendees offered positive feedback on the two seminars. Similar seminars in partnership with other academic departments will be scheduled in the future to address topics identified by the advisory committee.

In the past, MRSEC collaborated with materials-related academic departments to sponsor master classes, taught by CMSE research scientist and science image specialist Felice Frankel, that focused on the visual communication of science and engineering. The classes were designed to enhance postdocs' and graduate students' oral and visual presentation skills. Frankel has worked with scientists and engineers for many years and has published two books. Her book *Visual Strategies: A Practical Guide in Graphics for Scientists and Engineers* formed the foundation of the master classes, which consisted of a large-group lecture followed by small-group workshops. In June 2016, Frankel presented a workshop to MIT graduate-level students and postdocs on improving their technical skills and aesthetic sensibilities so that they could create engaging photos of their work. In addition, CMSE co-sponsored a seminar in July 2015, "Submitting Images to *Nature* Magazine," that consisted of a discussion with *Nature*'s art director, Kelly Krause, led by Frankel. The event was recorded for distribution online as part of the 0.111x Making Science and Engineering Pictures MITx course.

In addition to the seminar series, the MRSEC director has been meeting individually with postdocs to offer career development and job search advice. The Office of the Vice President for Research (VPR) oversees a robust program of mentoring and professional development activities for postdoctoral researchers that includes a seminar series, workshops, and a library of online resources. The office also supports the postdoc-led MIT Postdoctoral Association, which sponsors speakers, workshops, career fairs, writers' groups, and social events. The postdocs are informed of this broad range of opportunities through a listserv maintained by VPR.

Finally, as part of its postdoc mentoring plan, CMSE encourages postdocs to hone their science communication and presentation skills by teaching in the center's education

programs. In addition to mentoring REU students, they regularly participate in CMSE's middle school, high school, and teacher programs.

Administration, Management, and Research

Our MRSEC program is administered by a proactive and effective management team that responds quickly to emerging needs of the program. Currently, six administrative and seven SEF staff support the program. Administrative staff include an education officer, facilities and safety coordinator, financial administrator, assistant to the director, assistant director, and director. SEF staff include one technical associate, four research specialists, a research scientist, and a project technician. The CMSE director reports to the dean of engineering, the assistant director reports to the director, and all other staff, including the facilities manager, report to the assistant director. Our current director also serves as CMSE's chemical hygiene officer. CMSE currently has a faculty education program leader who marshals our educational outreach plans with our education officer and a faculty special projects coordinator who will work with MRET participants to develop hands-on teaching modules and related video content. The overall objective is to create a new pipeline of future engineers and scientists for fields vital to the future of the United States through the use of cutting-edge, hands-on learning exercises. For example, a collaboration with a local MRET teacher led to the development of an inexpensive ($50–$100) polymerase chain reaction machine that allows K–12 students to learn about DNA biotechnology.

CMSE Junior Faculty SEF Award

CMSE, recognizing the financial burden MIT junior faculty face in utilizing large experimental facilities for research needs, started a new award program in 2011 to assist these faculty members in accessing the CMSE shared experimental facilities. The faculty who were awarded funds during FY2012 found the program very helpful, and it was decided to continue the program into the future and extend each award for a two-year period, allowing more time for the junior faculty members to use this funding. Contingent on the availability of center discretionary funds (this program is supported by funds distributed to CMSE from technology licensing revenue) and the number of qualified applicants, CMSE will typically make awards to five or more MIT assistant professors each year at a level as high as $5,000 for each award. Each award will last for two years and can be applied only to user fees in CMSE shared experimental facilities. These awards are restricted to faculty engaged in research activities related to aspects of materials science and engineering as practiced at CMSE. One- to two-page research proposals for the awards will continue to be solicited from junior faculty throughout the MIT materials community each year and reviewed by the center director, who will make awards based on the strength of the faculty proposal and the financial need justification. The following MIT assistant professors (all from DMSE) received awards in FY2016: Betar Gallant, Rafael Jaramillo, Juejun Hu, Robert Macfarlane, and Cem Tasan.

MRSEC-Driven Materials Community Building Activities

CMSE, in collaboration with the Department of Materials Science and Engineering and the Materials Processing Center, continues to host a seminar series in materials science and engineering that started in 2005. The objectives of the series are to provide an op-

portunity for faculty, research staff, and students from the CMSE community to meet on a regular basis to hear about the latest breakthroughs in materials research and to inform the greater MIT community about materials research and the MRSEC program. Seven seminars were held during the fall of 2015. The speakers were Professor G. Arjun Yodh (University of Pennsylvania), Professor Michael Ward (New York University), Professor Melissa Hines (Cornell University), Professor Hui Cao (Yale University), Professor Evan Reed (Stanford University), Professor Alon Gorodetsky (University of California, Irvine), and Dr. Vladimir Liberman (Lincoln Laboratory Nanoscale Technologies Group). Speakers during the spring semester were Dr. Supratik Guha (University of Chicago and Nanoscience and Technology Division, US Department of Energy), Professor Zhenan Bao (Stanford University), and Professor Jill Millstone (University of Pittsburgh).

CMSE also hosts the MIT-wide Facilities Managers Group. This group was formed to better coordinate the synergistic activities of the large materials community at MIT. The CMSE director and one of the CMSE SEF managers, chosen each year by the CMSE director, chair the group, and meeting arrangements are made by CMSE headquarters staff.

CMSE Committees and Boards

CMSE activities are guided and supported by three internal committees and one external committee. The Committee on CMSE, Internal Advisory Committee, and Space Committee are internal MIT committees that offer guidance to CMSE on research, large equipment purchases, space, safety, and educational matters. The Science and Engineering External Advisory Board offers guidance on ways to enhance collaborations and supports major efforts in long-range materials research and engineering. The following individuals now serve on the board: Dr. Leonard Buckley, director of the Science and Technology Division at the Institute for Defense Analyses; Dr. Edwin Chandross, a materials chemical consultant; Dr. James Misewich, associate laboratory director for basic energy sciences at the Brookhaven National Laboratory; Dr. Rama Bansil, a professor in the Department of Physics at Boston University; Dr. Sharon Glotzer, Stuart W. Churchill Collegiate Professor of Chemical Engineering at the University of Michigan; and Dr. Raymond Samuel, assistant dean of the School of Engineering and Technology at Hampton University and an associate professor in the Department of Chemical Engineering.

Michael F. Rubner
Director
TDK Professor of Materials Science and Engineering