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. 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 working collaboratively in a team-based approach. To accomplish this important mission, CMSE enables collaborative, interdisciplinary research among MIT faculty and among MIT faculty and the researchers of other universities, industry, and government laboratories.

CMSE 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. From May 2016 through April 2017, 1,041 people used our SEFs, including 808 students and postdocs of MIT faculty in 18 academic departments, labs, and centers; 36 students and staff of faculty from 14 outside academic/research institutions; 180 students using the facilities for MIT lab subjects; and 17 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 2016, 83 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 2016–2017 academic year, CMSE supported three IRGs, one super seed, and four seeds, with four new seeds starting during the last four months of the year. The MRSEC grant supports 31 faculty from nine MIT departments and, through a subaward, one faculty member from the University of Central Florida. Selected research highlights from FY2017 are reported below.

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

IRG-I research is directed at the development of unique, multi-component nanostructured fibers and nanoparticles through the use of a newly discovered processing paradigm involving nonlinear fiber fluid instabilities. This group reports on the development of new methodologies for producing two-face (Janus) nanoparticles of silicon and germanium. This scalable process starts with an Si/Ge core/silica cladding fiber that is fed into a flame to induce the breakup of the core into individual liquid droplets. When solidification occurs, Si/Ge Janus particles are formed with potential application as micro- or nano-swimmers due to their asymmetric optical absorption properties or infrared photodetectors or solar cells due to their increased infrared absorption. This is the first time such structural control has been demonstrated with Si/Ge particles of this length scale.

In pursuit of multi-functional fiber probes with applications in neuroscience, the group has fabricated fibers that can be utilized for both electrical recording and optical stimulation of neural activity. This new fiber system contains hollow channels that can be used to deliver viral vectors and drug molecules directly to the site of neural activity. The composite, multi-material fibers are made up of micron-sized electrically conductive electrodes, optical waveguides, and microfluidic channels. With these fibers, microfluidic viral delivery of a blue-light sensitive channel rhodopsin was used to demonstrate optical control of neural activity in the cortex of a mouse and correlated with increased locomotor activity. IRG-1 researchers also fabricated highly flexible hybrid probes that can be utilized to record and optically excite neural activity in the spinal cord of a mouse. The low bending stiffness of these fibers permitted chronic implantation into the mouse spinal cord, allowing neural recordings for a period of at least three weeks with negligible foreign-body response. The development of these highly versatile, multi-functional fibers provides exciting new capabilities to those studying the workings of the nervous system.

Plasmonics is an exciting new area with potential applications in novel electro-optical devices. In many of the envisioned applications, however, material losses from metallic nanoparticles limit the full capabilities of these systems. IRG-1 researchers have

theoretically demonstrated that an approach involving dielectric nanoparticles on metallic films can produce a unique combination of strong fields and high confinement along with small dissipative losses, opening the door to the development of hybrid plasmonic dielectric resonators. This group has also put forth an expanded theoretical framework to describe for the first time how compact, optically pumped far-infrared (OPFIR) lasers work in high-pressure operations. Results from theoretical modeling and experimental measurements match almost perfectly and demonstrate that these lasers can achieve a very high quantum efficiency level up to 80% of the Manley-Rowe limit. The output power of these lasers is about an order of magnitude larger than that of commercially available OPFIR lasers with a volume that is 1,000 orders smaller.

IRG-I is establishing a wide-ranging, materials-agnostic fiber fabrication approach that can be used to create multi-component fibers with advanced optical and electrical capabilities as well as scalable, well-defined nanoparticles with complex morphologies. 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. On the fundamental side, this research offers a new paradigm for fluid-dynamic studies through the use of highly controlled environments for 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

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 (known for their amazing selective filtration capabilities), it has been found that the detailed spatial localization of charged amino acids with respect to hydrophobic phenylalanine-glycine (FG) domains governs the selectivity of FG-based gels by tuning the substrate recognition and self-assembly of the hydrophobic domains. This research shows that charge type and placement of amino acids regulate self-assembling hydrophobic domains, with important implications for the creation of structures that regulate both the mechanical and functional properties of self-assembling polymer networks and hydrogels.

IRG-II researchers have developed an oil-in-water, nano-emulsion-based thermo-responsive "ink" with rheological and photoreactive properties that can be used in stereolithographic three-dimensional (3D) printing. They demonstrated that hydrogels with multiple length scales spanning nanometers to millimeters can be printed with high fidelity. Post-processing of the printed samples was further used to generate mesoporous hydrogels that serve as size-selective membranes. This new approach to 3D printing of self-assembling gels can be used to control the structural dimensions of gels from nanometers to centimeters.

In pursuit of hydrogel systems with tunable metal-coordinate cross-link dynamics, IRG-II researchers have shown that simple adjustments of the concentration of the coordinating metal ions allow easy tuning of both the gel plateau modulus and relaxation times. This versatile hydrogel engineering platform was further expanded by exploiting the sensitivity of metal-coordinate cross-links to free radicals, thereby creating hydrogels with ultraviolet-responsive visco-elastic properties. Another polymeric gel system under investigation is based on metal-organic cage (polyMOC) nanoparticles incorporated into block copolymers (BCPs). The resulting "block co-polyMOC" materials feature microscopic structures and mechanical properties that can be readily tuned by adjusting the size and geometry of the cage component and the composition of the BCPs. Star polymers were fabricated by controlling the ligand geometry and metallosupramolecular assembly. Researchers from the group have also developed an efficient synthetic route to "A-branch-B" Janus bottlebrush polymers. A large number of these polymers were synthesized and investigated for their bulk and thin-film self-assembly abilities. Armed with new materials with controllable structures and a new loop-counting method, the researchers derived a real elastic network theory that describes how loop defects affect bulk elasticity, shedding new light on a long-standing issue in the quantitative theory of elasticity.

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 cross linking, 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

IRG-III research seeks to discover the coupling mechanisms between oxygen defects and the transport of phonons, spin, and charge at the interfaces of metal oxides. Theoretical studies aimed at understanding the effects of mechanical stress and electric fields on the defect chemistry (particularly oxygen defect types and concentrations) in transition metal oxides have demonstrated that it is possible to tune the electronic conductivity of metal oxides via the application of stress. The group's ability to execute electronic structure calculations under high electric fields allowed it to further explore the effects of electric fields on oxygen vacancies in a model oxide system. A new thermodynamic formulation was developed to quantify the defect formation energetics in an insulator under a high electric field.

IRG-III researchers have developed a new means of tuning the crystal and electronic structures of functional oxides by using electrochemical potentials to control the

oxygen content in the oxide. The aim is to trigger a phase transition electrochemically and obtain distinct physical and chemical properties. In a model SrCoOx system, an electrochemically triggered phase transition between two distinct crystal structures of this material was successfully demonstrated. This electrochemical method of controlling phase and properties is applicable to a wide range of oxides with multivalence and associated distinct phases. For example, this group has now shown that VOx exhibits a newly discovered electrochemically controlled metal-to-insulator transition between V2O5 and VO2. This transition can be triggered from room temperature to 100°C, facilitating high-temperature electronics for automotive or aircraft applications.

Researchers from the group also examined the coupling of ionic defects with phonons and the use of electrical fields to control phonons via ion migration in SrCoOx. Previous measurements of the thermal conductivity of SrCoOx suggested an increasing conductivity with increasing applied voltage as SrCoOx undergoes the solid-solid phase change from brownmillerite to perovskite. New results provided further evidence for the dependence of thermal conductivity on an electrically induced phase change of the material, an increase in thermal conductivity from brownmillerite to perovskite with increasing anodic voltage. Voltage-controlled formations of oxygen vacancies and their effects on magnetism at a ferromagnetic metal/metal-oxide interface have also been studied in Co/oxide thin-film stacks for a variety of oxide materials. Devices fabricated from these materials reveal that, at zero gate voltage, the Co layer exhibits strong perpendicular magnetic anisotropy and a square out-of-plane hysteresis loop. When the gate voltage is applied above a threshold, the magnetization switches to in-plane orientation and oxygen vacancies cause darkening of the oxide. The bixbyite structure of rare-earth oxides appears to be essential in observing these interesting voltage effects.

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 magnetoelectronic 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).

FY2017 Super Seed Research: Magnetically and Optically Driven Topological Semimetals

Topological semimetals (TSMs) are a newly discovered phase of matter analogous to topological insulators but with non-insulating band structures. This group has synthesized single crystals of the TSM candidate ZrTe5 using a vapor transport method and measured the electronic structure using photoemission spectroscopy. The observed small Fermi surface is consistent with electronic transport measurements and suggests that the Fermi level is positioned near the band edge.

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

FY2017 Seed Research

- Seed 1: Chemically Modified Carbon Cathodes for High Capacity Li-O2 Batteries (Yogesh Surendranathm, Chemistry). This seed seeks to improve the long-term performance of Li-O2 batteries by developing electrode surface treatments that inhibit the growth of insoluble Li2O2 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.
- Second Grant Seed Competition: For our second seed competition, we received 16 proposals from six different MIT departments; 13 were from assistant professors. Proposals from the following four assistant professors were chosen for awards: Jennifer Rupp (DMSE), Robert Macfarlane (DMSE), Luqiao Liu (EECS), and Riccardo Comin (Physics).

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 April 2017, 1,041 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.

The SEF staff has been an important element of many of our educational outreach programs and enthusiastically embraces this role. For example, our staff play a special

role in the training of MIT graduate and undergraduate students and our summer educational outreach participants. During this academic year, about 180 undergraduate students used the facilities as part of their laboratory subjects.

SEF staff members offered a number of mini-courses during MIT's 2017 Independent Activities Period (IAP) to train students to operate SEF equipment and apply the latest techniques to their research problems. In January of 2017, a total of seven courses were offered to the MIT community.

Materials Research Facilities Network

During FY2017, 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 enables students and faculty who do not have access to instruments such as those at our SEFs to visit MIT so that they can learn about and 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 SEFs.

During the summer of 2016, Dr. LaShanda Korley from Case Western University sent two PhD students to MIT to use the analytical, electron microscopy, and X-ray facilities to study self-assembled fiber networks and polymer peptide hybrids. In March 2017 Professor Joan G. Lynam from Louisiana Technical University, along with a graduate student and two undergraduate students, came to MIT to use these facilities to study potential sustainable cement additives. Also during March, Professor Kimberly Stieglitz from Roxbury Community College (RCC) in Boston brought a student to MIT to use the X-ray facility, and Dr. Ellie Fini from North Carolina A&T State University came to MIT with one student and one research associate to use the electron microscopy facility to continue her studies on asphalt additives.

During this reporting period, with funding from Professor Cem Tasan, the Lord Foundation, CMSE discretionary funds, DMSE, the Office of the Vice President for Research, and the School of Engineering, construction began on a new SEM in situ analysis user facility. When it is fully functional, the facility will allow in situ scanning electron microscopy (SEM) uniaxial tension, compression, bending, nano-indentation, and electrical property characterization tests as well as additional novel in situ SEM experiments.

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 more than 80 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.

MRSEC-supported faculty presented overviews of their CMSE research at three ILP-sponsored conferences: the 2016 MIT Research and Development Conference (Professors A. Belcher, N. Holten-Andersen, and K. Van Vliet), the 2017 MIT Japan Conference (Professor K. Ribbeck), and the 2017 MIT Europe Conference (Professor S. Leeb). In total, these conferences were attended by more than 1,000 researchers. Over the past year, seven new patents related to MRSEC have been issued, and eight new patent applications are pending.

In October 2016, 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 enables CMSE to highlight MRSEC-funded research and connect this research directly to managers and researchers from industry and government laboratories. The title of this year's Materials Day was "Materials for Electrochemical Energy Storage." The meeting was attended by approximately 180 registered guests from industry, government laboratories, hospitals, MIT, and other universities, as well as additional researchers and students from MIT. Representatives from more than 70 US and foreign companies, laboratories, and universities attended the event. The capstone poster session included posters from CMSE students and others from the MIT materials science community. This year, out of the 42 posters submitted, 24 originated from students and postdocs of faculty supported by CMSE funding. 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, 16 new patents related to MRSEC have been issued, and 19 new patent applications/provisional patents are pending.

The center's MRSEC-supported faculty enjoy a high level of outside collaboration. In its June 1, 2017, report to NSF, CMSE noted 47 collaborations (30 of which were international): three industrial collaborations, 41 collaborations with outside academic researchers, and three 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 that impact high school students and teachers as well as 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 and with religious communities and professional organizations.

For the past several years, CMSE has collaborated with Roxbury Community College 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 18 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 enabled class visits to MIT, K–12 school presentations by MRSEC researchers, and student involvement in research. For instance, chemistry teacher 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. Also, Doug Shattuck, a participant in the 2012 and 2013 MRET programs, has established an ongoing collaboration between Markus Buehler's research group at MIT and members of an after-school research team of his students from Concord Middle School to study mechanical properties of web construction. For the past two years, Concord students (who have named themselves the "Spider Team") have designed and conducted their own research at the school. Each spring they have come to MIT to report their findings and discuss the project with Buehler's

research group of graduate students and postdocs. In summer 2016, the middle school students prepared a poster that one of them presented at the national Microscopy and Microanalysis conference.

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 16th time in the summer of 2016. 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 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. Three teachers participated in the 2016 STEP.

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 14 years, this has been an extremely successful collaboration. WTP alumni report that this motor-building lab is an exciting part of the program. CMSE continued to support WTP by providing the curriculum and supplies for this part of the program in 2016 and will again do so in 2017.

Workshops and Public Events

MRSEC faculty and students contributed content to programs on campus and at local public events. For example, Professor Steven Leeb conducted educational activities at Winnbrook Elementary School's Math Night, attended by approximately 150 parents and students. Also, as he has done for many years, Professor Leeb taught a four-day class on materials and energy to 50 high school students on campus to participate in the Research Science Institute during June 2017.

In addition, Professor Al Grodzinsky's group demonstrated biomaterials and tissue engineering to 10 high school students and their teacher from the Dana Hall School for Girls. Professor Paula Hammond and members of her group presented experiments related to energy research to 12 members of the Science Club for Girls during a fall 2016 visit to her lab. Professor Caroline Ross' Nanoobservatory offered hands-on demonstrations of various nanotechnology instruments to about 60 high school students, teachers, and members of the public during Cambridge Science Week 2016. In February 2017, Professor Harry Tuller's student Michael Campion taught an elective course on green energy to 15 high school students. He also presented a talk on green energy and climate change to 120 students at Mahomet Seymour High School in April. Members of Professor Yogesh Surrendranath's research group led a discussion of electrocatalysis and demonstrated electrodepositing of cobalt phosphate films and catalyzed water splitting reactions to 20 students at East Boston High School in March 2017. Fourth- to sixth-grade students participating in MITxplore visited the campus in March 2017, and graduate students in the research groups of Professor Gang Chen and Professor Tuller offered math-based activities to about 60 of them.

CMSE worked with the Boston Area Girls STEM Collaborative to present a program for high school girls in March. "Science, Engineering and Technology (S.E.T.) in the City" provided 150 young women with a full day of lectures, panel discussions, tabletop activities, and lab projects at local universities. Finally, a group of MRSEC graduate students presented a polymers workshop to a group of 32 international middle school students from the Nord Anglia Schools who visited MIT in May 2017.

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 25 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 2016, 16 seventh- and eighth-grade students attended with their science teachers. Five of them were girls and eight were members of underrepresented minority groups. The students participated in hands-on activities presented by faculty, staff, graduate students, and undergraduates. The 2016 program included classes on ultraviolet light, simple DC motors, electric circuitry, polymers, glass blowing, metal casting, and solar cells.

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, and some of them work on MRSEC research. During this reporting period, MRSEC directly supported three undergraduates. CMSE faculty report that an additional 10 students (including five women and two minority students) 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 160 applications for the summer of 2016, 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 11 students accepted into the program for the summer of 2016 included seven women and three 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, two students supported by STARnet Research who were on campus to engage in work with MRSEC faculty member and IRG leader Caroline Ross joined in with the REU 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 five students participated in 2016, one of whom was female and two of whom were minority students. 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, 39 (66%) of the participants have proceeded to pursue bachelor's degrees. Of those, seven have enrolled in graduate programs in science and engineering. An additional student went on to medical school and is now serving her residency. Nine CCP participants proceeded directly from community college to employment. Five students continue at community colleges, and the status of five other participants is unknown.

For the past three years, MRSEC has broadened the impact of its community college partnerships by collaborating with Professor Polina Anikeeva to engage BHCC and RCC faculty and students in her lab's research. With CMSE support and her NSF CAREER grant funds, she hosts two students and a professor from these two community colleges each summer. The students participate in the center's REU program, and the faculty take part in the MRET program. In addition, Professor Anikeeva presents lectures and seminars at the community colleges during the academic year.

Partnership with Universidad Metropolitana

In 2008, MRSEC formed a collaboration with Dr. Juan Arratia at the Universidad Metropolitana (UMET) to enhance the research experience 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. Five others have completed their bachelor's degrees and are employed: three as engineers, 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. Four of the six participants in the 2016 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 2016 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, 15 postdoctoral associates worked on MRSEC research and 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 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 five research specialists, a research scientist, and a project technician. The CMSE director reports to the vice president for research, 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 works with MRET participants to develop hands-on teaching modules and related video content. The overall objective is to create a new pipeline of engineers and scientists for fields vital to the future of the United States through the use of cutting-edge, hands-on learning exercises.

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 received awards in FY2017: Riccardo Comin (Physics), Julia Ortony (DMSE), Luqiao Liu (EECS), Admir Masic (DMSE), and Jennifer Rupp (DMSE).

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 opportunity 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. During the fall of 2016 and spring of 2017, the center also collaborated with DMSE and MPC to welcome a wide variety of speakers from outside MIT to meet with CMSE faculty and students and to deliver lectures to which the entire MIT community was invited. These lectures typically drew audiences of 50 to 125 people. In addition, to promote inter-MRSEC interactions, researchers from other materials science centers are frequently invited to make presentations. This year's speakers were Supratik Guha (University of Chicago and Argonne National Laboratories), Zhenan Bao (Stanford University), Jill Millstone (University of Pittsburgh), Christopher Murray (University of Pennsylvania), Krishna Rajan (University of Buffalo), Luigi Colombo (University of Texas at Dallas), Joseph Davidovits (Institut Géopolymère), Nicholas Abbott (University of Wisconsin), Ali Javey (University of California, Berkeley), Anthony Rollett (Carnegie Mellon University), Ondrej Krivanek (Nion and Arizona State University), Sieu Ha (HRL Laboratories LLC), David Mitzi (Duke University), Daniel Gianola (University of California, Santa Barbara), David Pine (New York University), and Jennifer Dionne (Stanford University).

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.

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