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 September 2008, the NSF awarded CMSE a renewed six-year, $19.2-million MRSEC center grant to fund CMSE's research and educational outreach programs as well as its shared experimental facilities from September 2008 to August 2014. This award was the culmination of an extensive two-year internal and external review process and proposal preparation at CMSE headquarters, which enabled CMSE to compete with over 100 other national institutions to win one of 14 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 180 faculty members in 13 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 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, shared experimental facilities, 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 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 first four-and-a-half years of our 2008–2014 MRSEC award, researchers published results in 342 papers and were awarded 34 patents related to their MRSEC research with 60 more patents pending.

Our SEFs are used by numerous research groups from MIT as well as by outside academic and industrial communities. During March 2012 to February 2013, 1,149 people used our SEFs, including 854 students and postdocs of MIT faculty in 25 academic departments, labs, and centers; 64 students and staff of faculty from 14 outside academic/research institutions; 220 students using the facilities for MIT lab subjects; and 11 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 2012, 116 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. More than 650 people attended workshops and public events in which CMSE took part.

Interdisciplinary Research Programs and Scientific Accomplishments

The MRSEC grant supports three interdisciplinary research programs (IRGs), two initiative projects, and five seed projects involving 36 principal investigators. The research results for all groups funded in FY2013 are reported below.

IRG-I: Design of Nanomaterials for Electrochemical Energy Storage and Conversion

The supply of sustainable energy is arguably the most important scientific and technological challenge in the 21st century. Meeting this challenge will require not only increased energy efficiency but also new energy storage platforms to displace existing carbon-based fuels with carbon-neutral energy such as solar energy. Electrochemical devices such as lithium (Li) batteries and fuel cells that operate on hydrogen produced from solar energy are promising technologies to buffer the supply and demand of energy, particularly for portable power and hybrid propulsion in transportation. Meeting the demands of these applications requires new ideas to design materials with tailored reactivity toward lithium for Li batteries, and catalysts with markedly higher activity towards oxygen reduction reactions (ORR) in fuel cells. The objective of this IRG is, on the one hand, to use electrochemistry to accurately determine how thermodynamics, phase stability, and kinetics are modified at the nanoscale, and, on the other hand, to apply that knowledge to engineer materials with high-energy, high-power Li storage capabilities, and to design nanocatalysts with superior ORR activity and reduced noble metal content.

Faculty participants and department affiliations: Gerbrand Ceder, co-leader (Materials Science and Engineering [DMSE]); Yang Shao-Horn, co-leader (Mechanical Engineering); Angela Belcher (DMSE and Biological Engineering); Kim Hamad-Schifferli (Mechanical Engineering and Biological Engineering); Daniel Nocera (Chemistry); Troy Van Voorhis (Chemistry); Carl Thompson (DMSE).

IRG-1 Results

IRG-I members have investigated the role of oxygen electrocatalysis in the operation of non-aqueous batteries based on metal-air systems and carbon nanofibers. Disc and toroid-like distinct Li_2O_2 morphologies were observed at low current and high voltages as opposed to smaller Li_2O_2 particles (10–20 nm) at higher currents and lower voltages. Differences in the oxygen content of the surfaces of these different crystal shapes were found to influence the subsequent oxygen evolution (OER) kinetics during charging. This work demonstrates for the first time that the kinetics of charging of these battery systems is related to morphological aspects, thereby providing guidance to the desired nature of Li_2O_2 that will enable charging at lower overpotentials and produce increases in round-trip efficiency. On the theoretical front, first-principle calculations were used to investigate the fundamental origins of the overpotentials observed during charging of Li-O_2 batteries. This in turn, helped to identify a facile mechanism for recharging Li_2O_2. These results suggest that at the Li_2O_2 particle level there are no obstacles to increase the current density, and point to an exciting opportunity to create fast-charging Li-O_2 systems. Using a bio-templated synthetic approach, this IRG has demonstrated the formation of high aspect ratio manganese oxide (MO) nanowires wrapped in 1–3 wt % gold or palladium nanoparticles with compositions that outperform (in capacity and cycle life) materials made by mechanical mixing techniques. This new template is readily adaptable to other materials combinations, thereby providing a platform to test various catalysts for Li-O_2 batteries and other catalytic systems. In lithium-ion battery applications, researchers demonstrated that the utilization of redox reactions of pyrene derivatives incorporated into an electronically conductive carbon nanotube matrix is a promising strategy to design high-power lithium-ion battery positive electrodes that may overcome stability issues associated with the use of organic electrodes.

IRG-II: Mechanomutable Heteronanomaterials

This IRG seeks to develop a new class of “mechanomutable heteronanomaterials,” which are defined as possessing spatially localized and controlled nanoscale units of different types of materials that change their mechanical properties reversibly in response to an external stimulus. The use of heteronanostructures provides many exciting possibilities for mechanomutable materials design that have not yet been realized; in particular, high spatial resolution interactions with nanoscale objects and unique and amplified mechanical robustness. For this reason, this IRG explores the possibility of utilizing these materials as high-throughput, high spatial sensitivity tunable sensors (e.g., for cells, proteins, localized impacts, and pressure in liquids).

Faculty participants and department affiliations: Robert Cohen, co-leader (Chemical Engineering [ChemE]); Christine Ortiz, co-leader (DMSE); Mary Boyce (Mechanical Engineering); Markus Buehler (Civil and Environmental Engineering); Paula Hammond (Chemical Engineering); Krystyn Van Vliet (DMSE); Anna Balazs (University of Pittsburgh).

IRG-II Results

IRG-II researchers using a forest of nanotubes fabricated from layer-by-layer assembled polymers have identified a “stick-slip” mechanism responsible for a six-fold increase in the surface friction coefficient compared to the same system in the form of a uniform thin film. Modeling efforts confirmed this mechanism and predicted a viscoelasticity-induced friction coefficient similar to the experimentally measured values. These and related results confirm the fundamental hypothesis of this IRG: micro- and nanogeometry can be used in conjunction with stimulus-responsive materials to amplify and systematically tune mechanical properties. There are many examples of biological materials that respond to mechanical loads via chemical signaling over long ranges and along complex trajectories. Research in this group has now found that oscillating polymer gels (BZ gels) can also exhibit mechanical triggering and chemical “communication” across complex pathways. BZ gel disks were arranged on a surface in a T-junction. When the gel disk at the base of this T-junction was mechanically activated, it triggered the oscillation of all neighboring gel disks with signal splitting occurring at the "T" junction with no loss in signal amplitude. This work suggests the design of new systems for conversion of mechanical pressure into chemical information, thereby enabling novel sensors and transducers. Finally, the modeling of the micromechanics governing the instability of stiffer interfacial layers embedded in a soft matrix has suggested pathways to creating materials with reversibly wrinkling interfacial layers with possible applications to multi-functional active hybrid materials or actuating devices.

IRG-III: Multimaterial Multifunctional Nano-Structured Fibers

This IRG explores the materials science, design, fabrication, characterization, and potential identification of novel physical phenomena, of a unique class of fiber materials systems that are composed of conductors, insulators, glassy semiconductors, and especially crystalline semiconductors with more than 10-nm feature sizes. These fibers, while comprising all the essential crystalline semiconductor device attributes, are processed using conventional fiber draw processing approaches, thus yielding kilometers of fiber structures with engineered electronic, optical, thermal, and acoustic properties, and exploiting photonic bandgap phenomena wherever needed.

Faculty participants and department affiliations: Yoel Fink, co-leader (DMSE); Marin Soljacic, co-leader (Physics); John Joannopoulos (Physics); Steven Johnson (Mathematics); Erich Ippen (Electrical Engineering and Computer Science [EECS]), Ayman Abouraddy (University of Central Florida); Polina Anikeeva (DMSE).

IRG-III Results

IRG-III researchers have developed a new particle fabrication methodology that leverages the inherent scalability of fiber production to produce, with high efficiency and control, solid spherical particles having a unique set of sizes, shapes, and compositional characteristics. This new approach is an outcome of studies of in-fiber fluid instabilities once viewed as a challenge but now as an opportunity. The resultant particles are uniformly sized and controllable in the exceptionally broad range from 2 mm down to 20 nm. Their final structure is governed by the geometry of a drawn fiber core. Judicious design of the structures and composition of the fiber macroscopic preform makes it possible to create single-material solid spherical particles, core–shell particles, two-compartment Janus particles, and multi-sectioned "beach ball" particles. This development has significant implications for materials needed for photovoltaics, electronic devices, medicine and health-care, targeted drug delivery, chemical sensing and catalysis, photonics, and cosmetics. A variety of physical systems, including 2D optical fibers that display a Dirac dispersion relation, offer novel physics to be understood and exploited. Toward this goal, this IRG reports theoretical discoveries of frequency-isolated Weyl points and line nodes in gyroid 3D photonic crystals. This work potentially opens the door to new paradigms in photonics: topologically protected 2D chiral surface states, radiation-controllable enhancement by flat surface dispersions, possible new 3D topological phases of complete gaps, and novel transmission properties. Members of this IRG have also investigated the use of the optoelectronic fibers developed in this group to address the serious problem of spinal cord neural regeneration. The idea is to place neurons into hollow-core polymer fibers outfitted with electrodes and use these devices to achieve optoelectronic control and monitoring of developing neurons. Preliminary results demonstrate the ability to successfully culture healthy neurons within the fibers and to record their spontaneous and stimulated (with high potassium solution and bicuculine) activity.

Initiative-I: High-definition Nanomaterials— New Routes to 3D Hierarchical Nanostructured Materials and Devices

High-definition (HD) nanomaterials refer to a new class of 3D bulk material elements that can be tailored at the sub-nm scale by combining solution-based layer-by-layer (LBL) processing and related techniques (Cohen-Rubner) with the bulk 3D nanoporous carbon scaffolds recently developed and demonstrated as microfluidic elements (Toner-Wardle). While the applications for this work are manifold, this initiative focuses on developing a fundamental understanding of LBL assembly onto the 3D nanoporous elements, extending the recent space-constrained LBL of Cohen-Rubner to smaller spaces (accessible via aqueous routes) approaching single-nm dimensions, while simultaneously extending it from planar facing channels to 3D bulk nanoscale features, i.e., for an equivalent volume of channel. In essence, the LBL assembly process will now occur on 3D surfaces with 5–20X smaller constraint, and >2000% higher surface area. Bionanoelectromechanical system (BioNEMS) devices for bioparticle isolation will directly benefit from the surface modification provided by LBL as it will allow myriad new functionalities for the devices to be targeted, moving away from simply functionalizing to truly tailoring, and enabling new types of bioparticle manipulation. For example, a targeted device effort will seek to demonstrate LBL-enabled bioparticle capture and manipulation focusing on HIV, ~100nm in size. This capability is not accessible by state-of-the-art nano- and microelectromechanical system platforms. Success in such a device will lead to much broader investigations of nanoparticle-based information about disease processes in the body in future work, including enabling investigations of previously untargeted information packets in fluids (e.g., blood contains nm-scale exosomes in small quantities that could be used to track disease evolution and treatment effectiveness). This initiative work on LBL into bulk nanoporous elements will impact numerous other fields such as filtration, titration, and nanostructured anodes/cathodes.

The ability to tailor interfaces has led to many technological advances in materials in recent decades across all domains, and is particularly relevant when considering nanoscale effects. Biomedical research has particularly benefited from advances in surface chemistry and surface manipulation, enabling a large number of applications from controllable release/adsorption of proteins to affinity chromatography. Layer-by-layer deposition has emerged as a facile and flexible route towards layered molecular assembly, unlocking great potential particularly on films and surfaces. Extending LBL techniques to bulk materials with controlled nanoscale morphology is largely an unexplored area, and it is pursued here via a new route based on microfluidics for achieving 3D LBL assembly via solution-processing into nanoporous scaffolds.

Faculty participants and department affiliations: Brian Wardle (Aeronautics and Astronautics); Robert Cohen (Chemical Engineering); Michael Rubner (DMSE); Mehmet Toner (Health Sciences and Technology).

Initiative-I Results

Initiative-I researchers have successfully assembled nanoscale polymer multilayers onto individual carbon nanotubes contained in patterned arrays within microfluidic devices. The arrays are comprised of nano-separated, aligned carbon nanotubes (CNTs) that are patterned into macroscopic elements with unusually high porosity (~99%) and high permeability to aqueous solution. The resultant conformal coating is rich in primary amines that can be further functionalized to allow the capture and detection of biological markers. For example, a biotinylation functionalization protocol has been used to selectively capture nanoparticles on the nanotubes. This work moves the group one step closer to developing a versatile lab-on-a-chip platform for the capture of viral particles such as HIV.

Initiative-II: Quantum Optoelectronics and Spintronics with Topological Insulator Nanoscale Devices

The aim of this initiative is the development of topological insulator (TI) materials suitable for electronic, magnetic and optical devices. TIs represent a novel paradigm in condensed matter physics, where materials are classified according to the topological order of their band structure. TI devices are expected to allow the investigation of a variety of new quantum phases, and to open a broad range of spin-based functionalities. The studies carried out as part of this initiative are focused on the development of TI devices fabricated from thin films, and on development of sensitive techniques for spin mapping of TI materials. The ideal TI would be an insulator in the bulk and support electronic transport only through its topological surface states. In the present generation, TI materials such as Bi_2Se_3 are plagued by a finite carrier density in the bulk. The presence of these carriers limits the applicability of TI devices and hinders the study of surface effects. Growth of TI thin films in high-vacuum conditions is a promising approach to address these problems. It is also a particularly useful strategy for device fabrication since it offers fine control over geometry and composition and allows the growth of heterostructures.

Faculty participants and department affiliations: Pablo Jarillo-Herrero (Physics); Nuh Gedik (Physics); Jagadeesh Moodera (Francis Bitter Magnet Lab).

Initiative-II Results

Using an epitaxially grown Bi_2Se_3 device, a discrepancy in the location and shape of an observed minimum in conductance and capacitance was observed. This is related to the Dirac point of the surface state and is predicted to arise due to details of the band structure and disorder potential. Further, the growth of the Bi_2Se_3 thin films was optimized, with films reaching carrier mobilities close to 2000 cm^2/Vs, on par with results from leading groups in the field. The magnetic and transport properties of high-quality epitaxial TI thin film heterostructures were investigated by coupling with other systems such as ferromagnets. A new approach utilizing a proximity-induced internal field from a ferromagnetic insulator was used to create an exchange gap in the Dirac surface states of a TI. This is an important step forward in unveiling exotic properties, such as the quantized anomalous Hall effect, the topological magnetoelectric effect, and Majorana fermions.

Seed Research

Seed-I: Bioinspired Environment-responsive Ligand-coated Nanoparticles

Goals: This project seeks to understand, from a theoretical standpoint, how synthetic soluble nanoparticles can fuse reversibly (or irreversibly) with a cellular membrane and behave as membrane proteins. This effort was inspired by work on ligand-protected gold nanoparticles that has shown that such nanoparticles translocate across the lipid bilayer and insert themselves into cells [Verma A, et al. Surface-structure-regulated cell-membrane penetration by monolayer-protected nanoparticles. *Nature Materials*, 2008;7(7):588–595].

Accomplishments: During the first year of this seed, investigations were focused on nanoparticles that can rearrange their ligand shells by means of globally rearranging the anchoring of the different ligands. Research with this model showed that penetration was possible within a window of NP-bilayer interactions as well as ligand (hydrophilic)/(hydrophobic) interactions. This research resulted in two publications. During the past year, nanoparticles were studied that cannot undergo global rearrangements but instead only local rearrangements due to the flexing of ligands all in one direction and exposing hydrophobic areas. The idea is that when the particles insert or fuse with the bilayer they open a hydrophobic band by "snorkeling" their charged ligands (silver groups) out of the bilayer. There has been particular interest in understanding if the morphology of the ligand shell, meaning the rearrangement of the hydrophobic and hydrophilic ligands, affects the fusion propensity. To address this, a series of different morphologies have been studied, such as striped, random, and mixed configurations. The results indicate that the morphology does not play a big role in the energetics of fusion, although it is still not clear if the structure has any importance in the kinetics of fusion. The calculations of this model were done using a newly implemented technique for computing free energy difference called MBAR (multi Bennett acceptance ratio). The theoretical results agree extremely well with the observed experimental sizes that complex with the membranes. Using the same algorithm it was also possible to study nanoparticle-nanoparticle interactions. In addition, research dealing with the ramifications of the model introduced above, and the structure of the lipids using all atom simulations is under way.

Primary investigator: Alfredo Alexander-Katz (DMSE).

Seed-II: Ordered Microporous Electrodes for High-power Sustainable Li-ion Batteries

Goals: This seed project aims to build novel organic electrodes for Li+ batteries from redox-active covalent organic frameworks (COFs). Owing to their innate porosity, which should allow efficient Li+ intercalation, COFs are expected to exhibit improved power density relative to other organic electrodes, thereby providing a sustainable alternative to current battery electrodes.

Accomplishments: Initial efforts were focused on the use of polyimides made from simple diamines and aromatic dianhydrides that feature redox-active carbonyl oxygens. Battery testing results on benchmark materials showed that these even exceeded the reported discharge voltage of 2.08 V and capacity of 237 mAh/g. Preliminary data with these revealed low discharge capacities of 25 mAh/g. This value is significantly less than the theoretical capacity, and the likely culprit is incomplete polymerization; imides are known to form very strong bonds (for instance, Kevlar is a polymer made from similar connections). These strong bonds are likely too irreversible to allow supramolecular ordering and crystallization as required in our original design of COFs with ion-conducting channels. Accordingly, alternative electroactive building blocks were sought that may be incorporated within porous COFs.

Hexahydroxyhexaazatrinaphthylene (HATNOH) and tetrahydroxy dibenzotetrathiafulvalene (THDBTTF) were targeted because both cores (hexaazatriphenylene and tetrathiafulvalene) had been extensively used in electronic materials and it was hypothesized that upon incorporation in COFs, these would also provide increased charge conductivity, thereby minimizing the necessity of a conducting binder and potentially increasing the charge density. The two monomers were successfully synthesized through multistep organic synthesis pathways and their incorporation into boronate-based COFs was attempted by reaction with benzenediboronic acid. Although materials with these building blocks have not been isolated thus far, it is well known that finding the conditions required to isolate such compounds often involves semi-combinatorial approaches. Nevertheless, this work has demonstrated that electroactive species such as derivatives of thiophenes can in fact be incorporated within COFs, and it is expected that similar approaches will be successful with HATNOH and THDBTTF. These synthetic efforts and the associated measurements of electrochemical activity toward Li+ insertion will be the focus of studies in the near future.

Primary investigator: Mircea Dinca (Chemistry).

Seed-III: Engineering and Patterning Multiscale Nanostructures with Synthetic Biology

Goals: Amyloids are aggregates of proteins or peptides with cross-beta structure and fibrillar morphology that assemble via a rate-limiting nucleation step followed by fibril extension. Self-assembly of amyloid nanowires is based on amino-acid interactions between individual subunits that are programmable via the underlying genetic code. This project aims to engineer curli fibers, which are surface-expressed functional amyloids found in *Escherichia coli*, and explore how genetic changes to the curli subunit, CsgA, affect its functional, chemical, and mechanical properties. Individual curli fibrils are ~3–4 nm in diameter, can grow to many microns in length, and can laterally associate to form larger bundles.

Accomplishments: The direct method involves making grooves on a substrate, depositing fibers on the surface, and then applying bending stresses on fibers that span grooves. The indirect method estimates the Young's modulus by extracting information from transmission electron microscopy images. Based on thermal fluctuations, the Young's modulus is calculated from the deviation of the shape of the fiber from the segment that connects its free ends. The indirect method is more convenient to apply, as it does not require intensive experiments to applying bending stresses to fibers. Thus, the aim of this work was to check whether the results from the indirect approach were consistent with the direct approach, such that one can use the indirect approach as a surrogate characterization strategy for libraries of fibers. The indirect method estimated the Young's modulus of the same curli fibers to have a mean of about 3 GPa and a median of about 2 GPa. Based on these results, one can see that the indirect approach can be used as a method for characterizing the mechanical properties of curli fibers with reasonable accuracy. The follow-up plan is to apply this technique to study libraries of engineered fibers.

Primary investigator: Timothy Lu (EECS).

Seed-IV: Atomic Layer Deposition for the Design of Novel Catalytic Materials

Goals: The objective of this seed project is to implement synthesis strategies using atomic layer deposition for the production of advanced catalytic materials with molecular control over the composition and/or placement of single- and multicomponent active sites. A collaboration with Cambridge Nanotech, a startup based on atomic layer deposition techniques developed by Roy Gordon at Harvard University, was established to perform the depositions.

Accomplishments: Water-tolerant Lewis acids are important materials for the activation of oxygenated compounds in bulk water. The location and environment of the active site determines their activity and stability; therefore, the rational design of the topochemical properties is critical to control reactivity. Of particular interest is the use of these materials in conjunction with co-catalysts to effect cooperative catalysis. In the context of carbohydrate conversion in bulk water, complex formation with inorganic salts induces changes in product distributions in equilibrium-limited reactions, for example, in isomerization and epimerization reactions for the production of rare sugars. This project demonstrated that the use of tin-containing zeolites with the Beta topology with borate salts promotes the selective epimerization of aldoses in aqueous media. Specifically, a 5wt% aldose solution with a 4:1 aldose:SB molar ratio reacted under mild conditions using catalytic amounts of Sn-Beta yielded near equilibrium epimerization product distributions. When the reaction was catalyzed by Sn-Beta without borates, no carbon backbone rearrangement occurred and the reaction proceeded by way of an intramolecular hydride shift as reported in previous studies.

The reaction mechanism investigated using 13C labeled sugars and NMR proceeds by way of a 1,2 carbon shift wherein a bond between C-1 and C-3 is formed, with C-1 moving to the C-2 position with an inverted configuration. Solid state 13C and 11B NMR confirm that the sugar-borate complex exists inside the pores of the beta zeolite.

These results indicate that the cooperative action of Sn-Beta and SB generates a highly active catalytic system for epimerization reactions that, unlike most epimerases, can be used to process a variety of sugars without the need for prior substrate functionalization and can operate at temperatures where the equilibrium is more favorable. This system has the potential to convert common sugars into rare sugars with significant advantages over biological routes and is more general than competing inorganic catalysts. Future work aims to elucidate the synergistic effect between pore size, isolated Lewis acid sites, and borate salts required to stabilize the intermediate in this reaction.

Primary investigator: Yuriy Roman (Chemical Engineering).

Seed-V: Electrical-field Controlled Bio-membranes for Efficient Water Desalination

Goals: Lipid bilayers, which are the basis for cell membranes, undergo a remarkable transformation under electric fields where small nanopores can be opened and closed. If this process can be properly controlled, then artificial membranes for filtration or desalination could be developed. The goal of this study is to model this complex behavior and eventually demonstrate filtration control of an artificial lipid biomembrane.

Accomplishments: In order to form a controllable biomembrane using biosurfactants, the chemical, mechanical, and electrical properties of such membranes need to be thoroughly understood. The focus of current work has been to understand the fundamental molecular components and interactions in lipid structures. Using a Langmuir trough, phase change between a solid-like and fluid-like regime has been observed and corroborated by atomic force microscopy and wetting experiments. During this seed period, the group has come up with a coexistence model of phase change. However, further experiments to observe phases in situ using such techniques as Brewster angle microscopy will be necessary to confirm this model. In addition, molecular dynamics simulations have shown the importance of lipid conformation and phase on wetting behavior.

The group has also undertaken a study in understanding the fundamental mechanism of boiling enhancement in surfactants, which could potentially bring improvements to existing phase change desalination technologies such as multi-stage flash. Boiling involves the nucleation of vapor bubbles, which is highly dictated by the surface morphology of the boiling surface, surface properties, and fluid properties. Boiling performance is characterized by the ratio of heat transfer to temperature difference. Thus, an enhanced boiling system can operate at lower temperatures, which can reduce energy costs and prevent high-temperature fouling in desalination applications. The common argument for enhancement with surfactants is simply the lowering of surface tension causing easier bubble departure. However, the group has shown that the overall heat transfer benefit from surface tension reduction is minimal and does not account for the significant enhancement (up to 200%) observed in experiments. Instead, a model has been developed which takes into account the adsorption of surfactants to the solid surface, and this model reasonably agrees with experimental data. Further experimentation with a larger variety of surfactants will help uncover specific molecular properties that are most relevant in enhancing boiling performance and help discover ideal surfactants for boiling applications including desalination.

Primary investigator: Evelyn Wang (Mechanical Engineering).

Multi-faculty Seed-VI: Soft-matter Hierachical Assemblies for Directed Energy Flows

Goals: This project seeks to develop antenna structures that are hierarchically organized to maximize and direct energy flows in the form of electron-hole pairs (excitons) and electrons and/or holes. The molecular control of the transport of excitons could revolutionize fields in which photon harvesting and energy conversion are key elements. The creation of the required hierarchical supramolecular assemblies with enhanced transport properties will be explored through the use of block copolymer templated chromophores.

Accomplishments: Four elements were investigated for this project:

- Chromophore selection
- Chromophore dispersal in block copolymers and supramolecular structures
- Graphoepitaxial templating
- Optical properties

In the previous year, chromophore and polymer selection was completed, and partial dispersal of the selected chromophore in the particular block copolymer was accomplished. Due to difficulties in forming J-aggregates in the block copolymers, the project has shifted gears and instead of using uncharged polymers, block copolymers with a charged block and a neutral block are being pursued. By exploiting electrostatic interactions (or coacervation) between oppositely charged chromophores, the formation of J-aggregates inside the domains of block copolymers has been realized. For this particular case, commercially available tetraphyenylporphyrin sulfonate (TPPS) was used, exploiting interactions between the anionic J-aggregates formed by these dyes and cationic block copolymers which contained a poly(N,N-dimethylaminoethylacrylate) (PDMAEA) block and poly(N-isopropylacrylamide) (PNIPAM) block to drive templating and coacervate self-assembly. The polymers were synthesized by reversible addition-fragmentation chain transfer (RAFT) polymerization. The properties of the free and confined dyes are similar, implying that J-aggregate structures are formed inside the block-copolymer domains, which were spheres in this case. The presence of J-aggregates can be clearly seen from the appearance of a high and narrow absorbance peak red-shifted from the peak in dispersed solution that occurs at ~450nm. The emission in this system, and both absorbance peaks at ~500nm and 700nm decay via the same pathway. These results represent the first steps in self-assembling antennas and organic electronic nanosystems with very precise properties.

Faculty participants and department affiliations: Alfredo Alexander-Katz (DMSE); Bradley Olsen (ChemE); Caroline Ross (DMSE); Timothy Swager (Chemistry); Marc Baldo (EECS).

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, Crystal Growth and Preparation, Electron Microscopy, and X-ray Diffraction—staffed by a team of highly motivated professionals. During the year ending February 2013, 1,149 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 per 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 has been an important element of many of our educational outreach programs and enthusiastically embraces this role. For example, staff members play a special role in the training of MIT graduate and undergraduate students and summer educational outreach participants. During this academic year 220 undergraduate students used the facilities as part of their laboratory subjects. Lab subjects included courses in the Departments of Chemical Engineering; Earth, Atmospheric and Planetary Sciences; and Materials Science and Engineering.

SEF staff members offered a number of mini-courses during MIT's 2013 Independent Activities Period to train students to operate SEF equipment and apply the latest techniques to their research problems. In January, 90 students and postdoctoral associates attended courses taught by the center SEF staff.

Launching of a New Shared Experimental Facility

With the $1,837,421 NSF American Recovery and Reinvestment Act grant to renovate 2,900 square feet of laboratory space in Building 13, a new energy-focused shared experimental facility has been created. The research tools housed inside the facility are supporting several large interdisciplinary programs including the Eni-MIT Solar Frontiers Center, MIT Solar Revolution Project, the Center for Excitonics (a Department of Energy–funded Energy Frontier Research Center [EFRC])), the CMSE-supported MRSEC, and the Solid-State Solar-Thermal Energy Conversion EFRC at MIT. The new facility is operating on the same business model as the other SEFs. The equipment purchased for this facility (funding provided by the Eni-MIT Solar Frontiers Center) includes an atomic force microscope, an inspection optical microscope, a 4-point probe, a variable-temperature He cryostat, a Ti-sapphire laser, and a tunable laser source, an infrared light source and monochrometer, a streak camera for visible light signals, an 85% humidity/85°C chamber, a 3D imaging Veeco Dektak, a multiglove box system containing a solar simulator system, a current voltage testing setup, a capacitance voltage testing setup, a multisource thermal evaporator, and a spin-coater. Construction of this new facility has been completed and the lab is operational. Through FY2013, 2,122 hours of instrument use were logged by users from 12 research groups at MIT from the Departments of Chemical Engineering, Chemistry, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, and Physics.

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 at least 64 meetings with representatives from a broad range of different 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 Apple, BP, Bosch, Coca Cola, Energizer, ExxonMobil Corporation, Johnson Controls Inc., Lockheed Martin Corporation, Mitsubishi Electric Research Laboratories, and Shell.

CMSE contributes to the showcase MIT materials event, the annual "Materials Day at MIT" program organized by the MPC. CMSE co-organizes the poster session and provides input on potential CMSE speakers. One important objective of this event is to connect MIT materials research to managers and researchers from industry and government laboratories. The title of the event this year was "Materials For Energy Harvesting." Professor Carl Thompson from CMSE/MPC provided introductory remarks and an overview of the program. Over 150 registered guests from industry, government laboratories, hospitals, MIT, and other universities attended the meeting, as did other researchers and students from MIT who joined in throughout the day. Representatives from over 50 US and foreign companies, laboratories, and universities attended. CMSE students and others from the MIT materials science community were well represented at the capstone poster event, with students and postdocs of faculty supported by CMSE funding accounting for 39 of the 86 posters submitted. The poster session was judged by a panel of members from MPC's Advisory Board, which includes research managers from industry. Two of the three winning posters represented work from three CMSE faculty: Carl Thompson, Robert Cohen, and Michael Rubner.

Professor Yoel Fink, MRSEC-supported faculty, presented an overview of his CMSE research in an ILP-sponsored conference: 2012 MIT Research and Development Conference. More than 250 representatives from companies including 3M, BAE, Chevron, EMC Corporation, General Electric, Goodyear, LG Electronics, Lockheed Martin, Michelin, Pfizer, Philips, and Samsung attended the conference. In addition, Professor Rubner presented an overview of CMSE research to a university delegation from Nigeria, and to a delegation from the Dutch-based multinational corporation DSM, which included top research and business administrators.

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 Kateeva, LumArray, Luminus Devices, OmniGuide, QD Vision, Svaya Nanotechnologies, and WiTricity Corporation. These 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. Recently, Sony announced that it would be using quantum dot technology from QD Vision in its next generation HDTVs. This represents the first mass-produced consumer electronic product containing quantum dots.

MIT's Technology Licensing Office is kept aware of new discoveries emanating from CMSE research and helps researchers file patents and issue licenses. During this reporting period, 10 new patents were issued; 23 new patent applications/provisional patents are pending that are related to the MIT MRSEC.

The center's MRSEC-supported faculty enjoys a high level of outside collaboration. During this funding period, these collaborations included four industrial collaborations, 39 collaborations with outside academic researchers, 18 international collaborations, and eight 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.

During the past year, the CMSE MRSEC established two international collaborations that currently engage multiple MRSEC-supported faculty.

For the past five years, MRSEC faculty have had an informal partnership with professor Marisa Beppu at the Universidade Estadual de Campinas, São Paulo, Brazil. During this time, Professor Beppu has worked with the MIT MRSEC to secure funding from Brazil that has enabled her and her colleagues to send four visiting students to MIT for periods ranging from six months to a year. This successful relationship has now been formalized into a partnership that will involve the exchange of students and expanded faculty involvement. To support this activity, CMSE recently applied for and received a travel grant from the MIT-Brazil Program that will support the travel of MRSEC graduate students to Brazil. These visits will promote knowledge transfer between CMSE research groups and the faculty at the Universidade Estadual de Campinas. Visiting MIT students will give a number of directed seminars and workshops and work with faculty in Brazil and at the MIT MRSEC to identify future collaborations. Currently, Professors Rubner, Cohen, and Hammond of the MIT MRSEC have hosted Brazilian students. In the latter case, Professor Hammond supported the postdoctoral work of Grinia Nogueira, the first graduate exchange student to visit MIT as a result of this relationship. Funding from the State of São Paulo Research Foundation will be sought to further expand this collaboration.

A new relationship with junior professors Ali Fuat Ergenic and Hulya Cebeci from Istanbul Technical University (ITU) was established during this past year. The objective of this collaboration is to support the development of junior faculty members from ITU and promote the exchange of ideas between the MIT MRSEC and this university. As a first step, professors Ergenic and Cebeci visited MIT in the summer of 2012 for several months to initiate collaborations based on the research of professors Rubner, Toner, Cohen, and Wardle, particularly the CMSE Initiative on layer-by-layer-enabled microfluidic devices. Working with MRSEC faculty, graduate students, and postdoctoral associates, professors Ergenic and Cebeci contributed to the CMSE initiative research program and worked to refine their ideas about their future research programs at ITU. New ideas were generated based on the CMSE Initiative interactions, and professors Cebeci and Ergenic wrote a successful proposal on “Fabrication of 3D Ultra Porous Micro and Nanostructures for Nanoparticle Exchange” that was funded as a full grant for three years by the Turkish equivalent of the NSF. At the end of their stay at MIT, Cebeci gave a joint CMSE/Harvard seminar called “Establishing Structure Property Relations from Nano to Macro Scale Composites with New Experimental and Modeling Routes” and Ergenic gave a seminar titled “Patterned Vertically Aligned Carbon Nanotube Micro Devices—Utilizing as Artificial Organs”. It is envisioned that, with suitable funding, this program will involve continued exchange of personnel and collaboration with ITU and the MIT MRSEC.

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 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, religious communities, and professional organizations.

For the past several years, through its Community College Program (CCP), 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. This dedicated NSF Experiences for Undergraduates (REU) program seeks 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 14 years, CMSE has operated a successful Materials Research Experience for Teachers 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.

Materials Research Experience for Teachers Participants, 2012

Name	School/subject(s) taught	Research project or lesson plan
Karla Brown	Jeremiah E. Burke High School Boston, MA (Biology)	Battle of the Bulbs: Lesson Plan for Middle School Science Class
Michael Dower	Young Achievers Science and Math Pilot School, Boston, MA (Science, Technology, and Engineering)	Spin Coating CdSe/ZnS Colloidal Quantum Dot Thin Films
Douglas Shattuck	Concord Middle School Concord, MA (Applied Technology)	Structure and Failure of Wood: A Computational and Micrographic Examination
Jill Sewell	Swampscott High School Swampscott, MA (Chemistry, Biology)	Light Scattering Measurements of Thin Film Thickness
Amanda Tsoi	Somerville High School Somerville, MA (Biology)	Engineering Mucin Functionalities Using Polyelectrolyte Multilayers
Sean Müller	Merrimack High School Merrimack, NH (Chemistry)	Track-Capacitive Sensing Floor Tiles

Relationships between CMSE and the MRET participants extend beyond the summer program. The teachers bring students to campus and arrange for MRSEC researchers to visit their classrooms.

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 11th time in the summer of 2012. STEP, subtitled "Dustbusting by Design" is a one-week workshop focused on increasing middle and high school teachers' content knowledge and providing them with experience in engineering design. The workshop correlates to the

Massachusetts state science learning standards. Participants spent the first three-and-a-half days in a machine shop on campus learning about the design challenges associated with the motor in a hand-held vacuum, then immersing themselves in the engineering design process as they constructed motors of their own design. The remainder of the week was devoted to presentations by CMSE researchers. In 2012, Professor Rubner talked about polymers and Professor Dinca presented his energy storage research. The lab portion of the program is 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 CMSE's MRET program, and through alumni of CMSE's education programs. Six teachers participated in the 2012 STEP, including three middle school science, technology, and engineering teachers and three high school teachers (one physics, one biology, and one biology and chemistry teacher). Two participants were women. Entrance and exit surveys were used to determine how well this workshop met the teachers' professional needs. All of the 2012 respondents indicated that they learned something new and useful for their classrooms during the week and that the program met or exceeded their expectations. They described applications of the experience in future teaching to include more hands-on design activities and utilization of the motor as part of the electricity and magnetism unit in the curriculum. One teacher commented that the program was "true professional development" and another described the workshop as "a very professional and appropriately rigorous program for adult scientists and thinkers that educate. One of the better professional development programs!"

A companion effort to STEP is CMSE's collaboration in the Women's Technology Program in EECS (WTP-EECS), a four-week summer residential program for 40 high school girls from across the country, during which the participants 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-EECS participants to join the lab portion of STEP to gain hands-on engineering experience. For the past 11 years, this has been an extremely successful collaboration. WTP-EECS alumni report that this motor-building lab is an exciting part of the program. CMSE continued to support WTP-EECS by providing the curriculum and supplies for this part of their program in 2012 and will continue to do so in 2013.

Workshops and Public Events

MRSEC faculty and students contributed content to a variety of programs and events on campus, at local schools, and at other public venues.

Professor Steven Leeb led science events with two different groups. In April, Professor Leeb presented an activity to 178 students and parents at the Belmont Winbrook Elementary School's annual Math Night. In addition, for the fourth year, he taught a four-session materials and energy class to 25 high school students in the Research Science Institute (RSI), held on the MIT campus. RSI is a well-established national six-week research program for outstanding high school students sponsored by the Center for Educational Excellence each summer.

Each April, CMSE participates in the annual Cambridge Science Festival, a nine-day, citywide public celebration showcasing the city as a leader in science, technology, engineering, and math. It includes a wide range of activities, including a science carnival featuring dozens of hands-on demonstrations. At the 2013 carnival, graduate and undergraduate students presented a series of demonstrations titled "Transforming into a Chemistry Superhero: Changes and Reactions." The presentation is typically attended by more than 200 people of all ages.

CMSE does not have a formal program to engage high school students in research on campus, but does match interested students with faculty-led research projects when feasible. Three high school students conducted research in CMSE groups during summer 2012. Two of these students came to CMSE through their teachers, who were former MRET participants. All three students presented their research at the CMSE summer poster session.

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 21 summers. The objectives 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 2012, 23 seventh- and eighth-grade students attended with their science teachers. Six of them were girls and 14 were members of underrepresented minority groups.

The students participated in hands-on activities presented by faculty, staff, graduate students, and undergraduates. The 2012 program included classes on glassblowing, light, simple DC motors, electric circuitry, polymers, solar cells, and electron microscopy. In group discussions at the end of the program, the students were able to satisfactorily explain the material presented during the week and identify new terms they learned during the program. On the exit surveys, participants indicated that they found the program fun and would recommend it to friends. Because the students are on campus from 8 am to 3 pm each day, meals are provided by CMSE. The center also provides bus transportation between the schools and the MIT campus.

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 work on MRSEC research part-time during the academic year and full-time during the summer. The MRSEC supports three students each academic term and three for 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. Over the past grant period, the MRSEC directly supported nine undergraduates. Three of them were women and two were underrepresented minority students. CMSE faculty report that an additional eight students (six of whom were women) worked on MRSEC research and were supported by MIT directly or worked for academic credit.

Undergraduate Research Opportunities Program Students funded by the Center for Materials Science and Engineering, June 2012–May 2013

Student	Department	Project title
Ryan Alexander	Electrical Engineering and Computer Science	Prediction and Validation of Unknown Crystal Structures
Tina Chen	Materials Science and Engineering	Probing Charge Transfer of Perovskite Catalysts Using a Facile Redox Couple
Daniel Gonzalez	Mechanical Engineering	Platforms for Power Electronics Education
Ethan Koether	Electrical Engineering and Computer Science	Educational Website for Learning the Subtleties of Electrical Engineering
Lucas Orona	Physics	Hybrid Topological Insulator Graphene Physics
Caitlin Sample	Materials Science and Engineering	Layer-by-Layer Assembly of PVA and Tannic Acid Multilayer Films
Brian Sennett	Electrical Engineering and Computer Science	Multi-Phase Water Flow Meter
Harini Suresh	Physics	Stimuli Responsive Polymeric Cell Microtubes
Prasanth Venkataram	Physics	Investigating Spontaneous Emission and the Density of States in Photonic Crystal Surfaces

Summer Research Internship Program

In collaboration with the Materials Processing Center, 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 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 2012, 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 15 students accepted into the program for summer 2012 included six women and nine men—six from underrepresented minority groups.

The students were paid stipends and worked full-time for nine weeks; most lived in a dormitory on campus. The nine-week summer internship program began with a three-day symposium during which faculty presented their research and described the projects available, then the interns selected their projects. Throughout the summer, they participated in weekly mentoring meetings devoted to research discussions and informal seminars with guest speakers on topics such as the graduate school admissions process, research funding, and intellectual property. The interns completed the program by producing posters that reported on their summer research. The resulting poster session was held during the final week and was open to the entire MIT community. It included posters produced by participants in CMSE's MRET and community college programs as well, and served the dual purpose of functioning as a final report by the interns and teachers, and informing the broader MIT materials community about the wide range of research supported under the auspices of the two centers. The CMSE/MPC program is well established as a quality internship program on campus. Consequently, other organizational units are seeking to fold their summer undergraduate researchers into the program. Last summer, the stipends of two students in the REU program were paid by the Department of Energy–funded Solid-State Solar-Thermal Energy Conversion Center. These two students were selected from the pool of applicants to the REU program and participated fully in the program.

Center for Materials Science and Engineering/Materials Processing Center Summer Interns, 2012

Name	Home institution/major(s)	Research project
Ethan Cottrill	Ohio University, Chemistry	Development of Siloxane-based O_2 Sensitive Materials
Jennifer Gavin	Florida State University, Mechanical Engineering	Manufacturing of a CNT-Modified Anti-Icing Aerosurface Leading Edge
Mina-Elraheb Hanna	University of Florida, Materials Science and Engineering	Design and Fabrication of an Axonal Guidance System
Chi-Sing Ho	University of California, Berkeley, Physics and Applied Mathematics	Microwalker Surface Binding Interactions
Scott Ho*	University of Utah, Mechanical Engineering	Electric Characterization of Topological Insulators
Ross Kerner*	University of Minnesota, Materials Science and Engineering	Josephson Tunnel Junctions with a Ferromagnetic Insulator Barrier
Anthony Kinslow	North Carolina A&T State University, Civil Engineering	Atomic Origins of the Mechanics of Carbon Materials
Jiexi Liao	Kennesaw State University, Biochemistry	Electric and Magnetic Control of $CoFe_2O_4/BiFeO_3$ Self-Assembled Nanocomposites
Cassandra Llano	University of Florida, Materials Science and Engineering	Screening for an Ideal Partnership between Mucins and Polyelectrolyte Multilayers
Eduan Martinez-Soto	Universidad Metropolitana, Applied Mathematics	Flexible and Protective Bio-Inspired Armor Systems

Eric Metzger	St. Olaf College, Chemistry	Synthesis of New Metal-Organic Frameworks Using Ditopic Ligands
Pablo Perez-Pereira	Universidad del Turabo, Mechanical Engineering	A Microfluidic Approach to Study the Effect of Nitric Oxide on Red Blood Cell Deformability
Rebecca Reitz	Brown University, Materials Engineering	Pulsed Electric Fields for Aqueous Electrophoretic Deposition
Margaret Stevens	Mount Holyoke College, Physics and Math	Layer-by-Layer Nanostructured Hybrid Solar Cells
Rodolfo Torres-Gavosto	University of Kansas, Chemistry	Novel Synthesis of Molybdenum Oxide Nanoparticles via Reverse Microemulsion

*Supported by the MIT Solid-State Solar-Thermal Energy Conversion Center, an Energy Frontier Research Center funded by the US Department of Energy, Office of Basic Energy Sciences, under Award Number DE-SC0001299.

CMSE participates in the MRSEC cross-site REU assessment. Intern responses on the 2012 survey indicate that overall the students felt the REU program was a positive experience that contributed to professional development and career plans. Eight-five percent of the interns rated the CMSE REU experience overall as either good or excellent and 90% indicated that they were likely to recommend the program to other undergraduates. Seventy-eight percent of the participants in the program felt their summer research experience increased their confidence in their ability to contribute to science, 90% reported feeling better prepared for graduate study as a result of the program, and 64% reported being more likely to enroll in a PhD program after the summer compared to their intentions before the program. Seventy-nine percent indicated that the REU helped clarify which field of study they wished to pursue in graduate school.

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 is another targeted REU program designed to enhance the diversity of undergraduate participants in MRSEC research and education programs and to broaden participation among science and engineering professionals. Four students from two local community colleges—Roxbury Community College and Bunker Hill Community College—that enroll significant numbers of minority students (55% and 40%, respectively) participate in CCP each summer. Over the eight years that the program has been in place, 73% of the 37 participants have been minority students and 59% have been women. One student with a disability participated.

Typically, community college students do not have the opportunity 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. To promote professional development, they also participate in weekly REU meetings to learn about intellectual property, the graduate school admissions process, and cutting-edge developments in materials research. The MRSEC director and education officer meet separately with the CCP students as a group at least twice per summer to discuss research and career plans. In these meetings, the students reported that their experience at MIT broadens their knowledge of possible science and engineering careers and provides a more realistic picture of graduate work. At least 73% of all former CCP participants who have finished their community college careers have enrolled in four-year colleges. Of those, one recently completed a master's degree in biotechnology, one has gone on to medical school, and two are enrolled in science PhD programs. A fifth student completed her BS in chemical engineering and is now working on her MBA while working at Abbott Laboratories.

In 2012, three participants were women and three were minority students. CCP students spent nine weeks on campus engaged in research as members of faculty-led groups, for which they received a stipend. They chose their research projects from several options presented by the MRSEC director during a preliminary seminar. CCP participants presented their research in the MRET/REU poster session in August. In addition to the four students funded by CMSE, two additional RCC students who had other support worked on campus in the labs of MRSEC faculty last summer and participated in all aspects of the CCP program; both were minority women.

Community College Program Research Experiences for Undergraduates Participants, 2012

Name	Home institution/major(s)	Research project
Share-Leigh Arneaud-Bernard	Roxbury Community College, Biological Sciences	Self Assembly of Artificial Chlorosomes
Diego Lopez	Roxbury Community College, Engineering	Synthetic Creation of a Chemotactic System via Utilization of Magnetically Actuated Microbiotic Walkers
Hajar Massaadi	Bunker Hill Community College, Engineering	Bio-inspired Flexible Scale Armor
Genesis Pena*	Roxbury Community College, Engineering and Liberal Arts	Functionalization of Carbon Nanotubes with Polyelectrolytes via Layer-by-Layer Assembly
Kamila Souza	Bunker Hill Community College, Engineering	Layer-by-Layer Self Assembly for Ceramic Nanocoatings
Jessica Spruill*	Roxbury Community College, Nursing	Engineering Amyloids in *Saccharomyces cerevisiae*

*Supported with non–Center for Materials Science and Engineering funds.

An ambitious plan is also in place to collaborate with professor Polina Anikeeva to build on the MRSEC's partnership with RCC and BHCC to reach more community college students. Using her NSF CAREER grant funds, Professor Anikeeva has developed a multiyear plan to engage BHCC and RCC faculty and students in her lab's research. Initially, one professor from each institution will spend a summer doing research with Professor Anikeeva's group as participants in CMSE's MRET program. CMSE will cover the stipends and provide Materials Research Facilities Network (MRFN) support (see below) to train participants to use SEF instruments to conduct research. The goal is for the RCC and BHCC faculty to integrate their learning into classroom teaching. Subsequently, Professor Anikeeva plans to make research presentations to community college classes. Finally, beginning in the second year, community college students will spend summers working in Professor Anikeeva's lab. This collaboration will extend CMSE's outreach to a wider group of community college students and faculty.

Partnership with Universidad Metropolitana

In 2008 the MRSEC formed a collaboration with Dr. Juan Arratia, director of Universidad Metropolitana (UMET), to enhance the research experience of students at the three Puerto Rican universities affiliated with the Ana G. Méndez University System (UMET, Universidad del Turabo, and Universidad del Este). Dr. Arratia refers students to the CMSE/MPC REU summer internship program. At least two intern positions a year are reserved for these students. A goal of this partnership is to recruit and retain science, technology, and engineering graduates from Puerto Rico. Since its inception, 10 students have participated in the program and another two spent two weeks at CMSE working with graduate students to learn to use research instruments in the SEFs. Five of the students are still completing their undergraduate studies. Of the others, two are working in science and engineering fields, one is a materials science and engineering graduate student at Rutgers University, and one is pursuing an MS at the Polytechnic University of Puerto Rico. 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. The objective of this local outreach component is to enthuse and encourage younger students to pursue higher education in science, technology, engineering, and math. In March, MRSEC director Michael Rubner visited Dr. Arratia in San Juan to discuss current programs, meet with this year's REU students, and explore future partnerships. He also made a presentation at the Universidad del Turabo that highlighted CMSE materials research including his work on anti-frost coatings.

Enhancing Diversity within Existing Programs

To increase minority participation in its REU summer internship program, CMSE directly advertises the program to minority-serving institutions. In fall 2012, approximately 450 letters with attached recruitment flyers were emailed to principal investigators at NSF-funded Centers for Research Excellence in Science and Technology, Historically Black Colleges and Universities' undergraduate programs, Model Institutions for Excellence, Louis Stokes Alliances for Minority Participation, and Tribal Colleges and Universities. CMSE also advertised its REU program via the Institute for Broadening Participation's online directory of REU programs. In addition, the education director encourages former minority participants to refer friends and other students at their home institutions to the internship program. The number of applications from women and minority students has been gradually increasing since the beginning of the grant. Applications recently received for the 2013 program showed a marked increase in the number of women (32%) and minority (14%) applicants compared to those in recent years.

Recognizing the importance of increasing 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 reaching its goal of having at least half the participants be teachers from schools attended by significant numbers of underrepresented students (>50%). Three of the six teachers in the 2012 RET program were from such school districts in Massachusetts (two from Boston and one from Somerville). In addition, CMSE directly engages Cambridge public middle school students through the Science and Engineering Program for Middle School Students. Students are drawn from schools where approximately 50% of the registered students are from underrepresented minority groups. Although the number of female and minority attendees varies from year to year, the program reliably reaches a diverse group of young people. Participation over the course of the current grant averages about 33% female and 54% minority students. In the summer of 2012, 26% of the participants were girls and 61% were minority students.

Partnership with North Carolina A&T State University

The MRSEC has also partnered with assistant professor of civil engineering Elham Fini at North Carolina A&T State University (NCA&T) to provide at least one REU slot to a student from this historically black university during the summers of 2012 and 2013. Professor Fini returned to MIT in 2012 to continue her collaboration with professor Markus Buehler. Dr. Fini's connections with MRSEC, along with a visit to CMSE by a group of her students in 2011, has resulted in the program's first applications from NCA&T students. Civil engineering major Anthony Kinslow participated in the 2012 program, and James Haynes, another civil engineering student, will join the 2013 REU cohort.

Materials Research Facilities Network Partnerships

With a supplement from NSF Materials Research Facilities Network funds, this year the MRSEC has strengthened its partnerships with these minority-serving institutions by providing access to its SEFs for their faculty and students. Exciting plans are in place for the faculty and their students to be trained to use the instruments to further their research projects beyond what is possible on their home campuses, and to build on that experience to enhance undergraduate teaching. Professor Fini will bring a postdoc and a senior undergraduate to CMSE in the summer of 2013 to use the X-ray diffraction and atomic force microscopy instruments. She expects this experience to enhance the their understanding of fundamental material characteristics and will incorporate the material into a graduate course she is developing on sustainable material characterization. Professor Oliva Primera at UMET will make use of the MRFN funds to expose her students to characterization techniques, bringing an undergraduate with her to CMSE to use the transmission electron microscope (TEM) and scanning Auger nanoprobe to characterize gold and silver nanoparticles and cadmium selenide quantum dots fabricated at UMET's Nanomaterials Science Laboratory (NSL). Back in Puerto Rico, the student will share the acquired knowledge with the rest of the students in NSL materials characterization workshops. Another UMET faculty member, professor Mitk'El

Santiago, plans to use CMSE instruments to characterize nanoparticles for solar energy harvesting applications. Two of his students will be trained to use the TEM and scanning Auger nanoprobe at the MRSEC to carry out the analyses. Professor Santiago will use the resulting data in his inorganic chemistry course of 20 undergraduates. All three faculty foresee incorporating the data into published research papers.

Postdoctoral Mentoring

CMSE has developed a robust postdoc professional development program. Over the past year, 21 postdoctoral associates—17 of whom are paid directly by the center—worked on MRSEC research. Postdocs participate in a director-led meeting to identify their professional development needs and topics they would like to see addressed; a postdoc advisory committee provides input to the director about activities and services that would be beneficial to their professional development. CMSE cosponsors a seminar series featuring annual professional development events. All postdocs working with CMSE faculty are invited to participate in the seminars, whether or not they are supported by the MRSEC. CMSE partnered with the Department of Chemical Engineering to present the 2012 seminar, the second since the seminar program began in 2011. At this event, a panel of faculty presented advice on finding and securing faculty positions. It included information on the search process, interviewing, and negotiating a startup package. The total number of postdocs attending these two events was 75.

Feedback from previous seminars indicated that the postdocs have found these discussions useful and value the personal experiences shared by the panelists. The postdocs also reported that they appreciated the opportunity to meet each other and discuss career issues in a collegial atmosphere. The MRSEC will continue to regularly present these professional development seminars based on topic suggestions from its postdoc advisory committee and event participants.

In addition to the seminar series, the MRSEC director has been meeting individually with postdocs to offer career development and job-search advice. The education coordinator is notified of the programs sponsored by the Office of the Vice President for Research (VPR) and regularly forwards the information to CMSE postdocs to ensure that they are aware of all professional development opportunities. The Office of the 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, including an information guide for new postdocs at the Institute. It 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 the VPR's office.

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. For example, Dr. Ling Lu of the Soljacic group developed a class on electron microscopy that he taught to the students in the 2012 middle school program. A classroom presentation and discussion of light and the principles of electron microscopy was followed by a demonstration of the scanning electron microscope in the Electron Microscopy SEF.

Administration, Management, and Research

Currently, seven administrative and seven SEF staff support the MRSEC program. Administrative staff includes an education officer, facilities and safety coordinator, financial administrator, financial and operations assistant, assistant to the director, assistant director, and director. SEF staff includes one technical associate, four research specialists, a project technician, and a research scientist. The CMSE director reports directly 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 has a faculty education program leader who marshals our educational outreach plans with our education officer.

CMSE Junior Faculty Award for Shared Experimental Facility Use

Four assistant professors at MIT received CMSE Junior Faculty SEF Awards in 2012, which assist junior faculty in accessing the CMSE shared experimental facilities. This program will be continued, with each award extended for a two-year period. Contingent on availability of center discretionary funds (this program is funded by monies distributed to CMSE from technology licensing revenue), CMSE will fund five to seven individual awards per year to MIT assistant professors at a level as high as $5,000 each. Each award will last for two years and can only be used for user fees in CMSE SEFs. These awards are restricted to faculty engaged in research activities related to aspects of materials science and engineering as practiced at CMSE. Research proposals for these 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 faculty received these awards for 2012:

Polina Anikeeva, Materials Science and Engineering

Silvija Gradecak, Materials Science and Engineering

William Tisdale, Chemical Engineering

Jeremiah Johnson, Chemistry

Other Meetings, Sponsorships, and Affiliations

CMSE has continued to support the joint CMSE/DMSE/MPC colloquium series, which allows the center to pool resources and bring in speakers from outside of MIT. The objectives of the colloquium 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. Five lectures were held in this grant period, including one speaker from the MIT MRSEC and four other speakers from around the country. The 2012–2013 speakers included professor Christian Santangelo (University of Massachusetts, Amherst), Professor Dinca (MIT), professor Ravi Bellamkonda (Georgia Institute of Technology), professor Thomas Epps III (University of Delaware), and professor Vidvus Ozolins (University of California, Los Angeles).

CMSE also continues to serve as a sponsor of the Boston Area CarbOn Nanoscience (BACON) meetings by providing funding for the food at these events. Professor Pablo Jarillo-Herrero is the organizer of the MIT portion of the programs. The BACON monthly meetings, now in their fifth year, bring together researchers in the Boston area to discuss their recent work and exchange ideas about carbon nanotube and graphene research in an informal setting. Each meeting consists of two talks (typically by students or postdocs) along with lunch and a coffee break. The talks are open to anyone and involve participant speakers from MIT, Harvard, and Boston University.

CMSE maintains a research collaboration with Dr. Fini of NCA&T, who holds a research affiliate appointment at MIT. In May, Dr. Fini visited with several of her students to participate in the MIT Materials Research Facilities Network project for which the MIT MRSEC has received a two-year supplement. Dr. Fini submitted a proposal to the MIT MRSEC titled "Investigating Phase Structure and Crystallization Pattern of Bio-Modified Rubber Asphalt Containing Nano-Clay" and received a $5,000 award from this MIT MRSEC supplement.

CMSE also co-sponsored the Forum on Materials for Sustainable Energy in March. This forum was intended to initiate a large-scale collaboration between MIT students, researchers, and faculty, and the Max Planck Institute for Intelligent Systems in Tübingen and Stuttgart, Germany. Other MIT sponsors included the DMSE, the MIT Energy Initiative, and the Office of the Dean for Graduate Education.

In addition, CMSE sponsored the Evolution of Colloidal Matter conference held at New York University in June. The conference featured talks by more than 20 distinguished members of the materials science community.

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. A meeting was held in February to discuss the CMSE experience with the CORAL facilities lab management program in the CMSE shared experimental facilities. The rollout of this comprehensive lab management system (which includes online user registration, real time instrument status, and a complete billing module) is now complete in all of the CMSE shared experimental facilities.

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 is an external committee that offers guidance on ways to enhance collaborations and supports major efforts in long-range materials research and engineering.

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