Materials Research Laboratory

The Materials Research Laboratory (MRL) was founded in October 2017 through a merger of the Materials Processing Center (MPC) and the Center for Materials Science and Engineering (CMSE), which together served more than 150 faculty and their research groups. Separately, the two centers served the broad MIT materials research community for nearly 40 years. By combining the expertise and activities of these preexisting centers, MRL enables the broad materials science and engineering community at MIT to conduct research that benefits society, helps companies and federal agencies address fundamental challenges, creates opportunities for technology transfer and practical engineering applications, and encourages collaboration through interdisciplinary research groups (IRGs), shared experimental facilities (SEFs), and educational outreach programs.

MRL encompasses research in areas including energy conversion and storage, quantum materials, spintronics, photonics, metals, integrated microsystems, materials sustainability, solid-state ionics, complex oxide electronic properties, biogels, and functional fibers. These are all interdisciplinary topics in materials. Each plays a critical role, with the focus on scientific discovery and how to design materials that lead to systems with improved performance or that enable new approaches to existing problems.

MRL also encourages interactions with industry through collaborative research and exchanges with visiting scientists, industrial internships, and educational opportunities. New interactions with industry include support of faculty engagement with four of the 14 USA Manufacturing Innovation Institutes. MRL sponsors a major annual workshop on topical areas of materials research involving both students and faculty. Materials Day, which includes a symposium and student poster session, is held each fall with invitations to members of industry and the community.

External Advisory Board

The MRL External Advisory Board, whose members come from industry, government, and academia, provides valuable advice on program development and management. It also assists in identifying opportunities for interactions with industry. The board meets for a full day after the Materials Day event each year. Meetings include presentations by members of the Institute's leadership on new research initiatives, and the MRL director and staff report on the prior year's activities and initiatives and goals for subsequent years. In addition, several new faculty members present their planned research at MIT, and senior faculty discuss major new initiatives. Faculty members who spoke at this year's board meeting included Krystyn Van Vliet—professor in Department of Materials Science and Engineering (DMSE) and associate provost, Carl V. Thompson—professor and MRL director, Geoffrey Beach—professor and MRL co-director, Vladimir Bulović—professor and MIT.nano founding director, and Cem Tasan—associate professor in DMSE.

The board meeting culminates in an oral and written report to the vice president for research or a designated representative. Current board members represent the 3M Corporate Research Laboratory, Lightweight Innovations for Tomorrow, Applied Materials, the Gateway for Accelerated Innovation in Nuclear, General Motors, IBM, Harvard University, Lockheed Martin Space Systems, Pellion Technologies, Saint-Gobain High Performance Materials, Sandia National Laboratories, the Semiconductor Research Corporation, The Boeing Company, and the wTe Corporation.

Internal Advisory Board

The MRL Internal Advisory Board membership is composed of faculty from across the Institute with a shared interest in interdisciplinary materials research. Board members include Professors Antoine Allanore, Ray Ashoori, Vladimir Bulović, Peter Fisher, Gene Fitzgerald, Karen Gleason, Lionel Kimerling, Elsa Olivetti, Katharina Ribbeck, Don Sadoway, Chris Schuh, and Harry Tuller. Members represent research communities from DMSE, Physics, Electrical Engineering and Computer Science (EECS), Biological Engineering (BE), and Chemical Engineering (ChemE), as well as the Office of the Provost and MIT.nano. These individuals serve a critical role in helping the MRL leadership identify key goals for the laboratory—including identifying and implementing new modes of engagement with industry, strengthening interdisciplinary research leveraging the National Science Foundation (NSF) Materials Research Science and Engineering Center (MRSEC) program model, and developing new capabilities and tool sets for the materials research community—and methods of achieving those goals.

Centers

MRL supports a number of interdisciplinary research centers by bringing together faculty from different disciplinary backgrounds, all with a common goal, to produce fundamental new science in materials research. As such, interdisciplinary research centers are usually created through faculty interest or in response to external funding opportunities. MRL provides administrative support to faculty to help facilitate those opportunities.

Materials Research Science and Engineering Center

The MRL 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 CMSE. In November 2014, NSF renewed a six-year $16.2 million MRSEC center grant to fund research and educational outreach programs as well as its shared experimental facilities from November 2014 to October 2020. This award was the culmination of an extensive two-year internal and external review process and proposal preparation that enabled CMSE to compete with over 150 other national institutions to win one of 12 NSF MRSEC awards for this six-year period.

During the 2018–2019 academic year, the MRL MRSEC research portfolio included three IRGs, and four single-investigator seed projects. The MRSEC grant supports 27 faculty from nine MIT departments and, through a subaward, one faculty member from the University of Central Florida. Selected FY2019 research highlights are reported below.

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

IRG-1 explores multi-material in-fiber fluid instabilities and is using the resultant knowledge to develop a new materials-agnostic fabrication approach for the creation of nanoparticles of arbitrary size, geometry, and composition. This work enables wide-ranging applications including opto-electronics, neuronal interfaces, and metamaterials design. In one example, they developed a new means to generate complex hierarchical structures embedded in hundreds of meters of functional fibers. As a demonstration, hundreds of light-emitting or detecting diodes were embedded and interconnected to illustrate fiber-to-fiber optical communication and heart rate monitoring in smart-fiber-based fabrics. The team also made significant advances in using thermal drawing to develop biocompatible microchannel fibers to serve as nerve guidance scaffolds, whose translation to clinical use has been hampered by fundamental materials and processing barriers. Through a combinatorial approach, they have produced structures with multiple microchannels and complex outer geometries and verified their efficacy through in vitro guiding of dorsal root ganglia neural cells. Finally, the team has developed a new theoretical framework to treat Maxwell's equations across multiple length scales to enable quantum corrections in designing and understanding multiscale materials.

Principal investigators (PIs): Polina Anikeeva (co-lead), Marin Soljačic (co-lead), Yoel Fink, John Joannopoulos, Steven Johnson, and Ayman Abouraddy (University of Central Florida).

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

IRG-II research seeks to gain fundamental insight into the molecular mechanisms that govern the structure-property relationships of complex biological hydrogels and use this knowledge to create synthetic mimics with similar extraordinary properties. Polymer networks designed from the bottom up with new structural motifs and chemical compositions can be used to impart dynamic features such as malleability or self-healing or to allow the material to respond to environmental stimuli. IRG-II has experimentally demonstrated cooperative self-assembly as a design principle by engineering topologically switchable gel networks using optical impulses. This photo switching produces coherent changes in several network properties at once, including branch functionality, junction fluctuations, defect tolerance, shear modulus, stress-relaxation behavior, and self-healing. The team has also elucidated the role of surface charge distribution in penetration of drug and protein gels and tissues, whose transport properties through gel networks are particularly critical to treatment of diseases such as osteoarthritis wherein effective transport through dense gel networks is required. In addition, IRG-II research has identified an equilibrium mechanism whereby gel-particle interactions lead to enhanced diffusion, providing new insights into particle dynamics in the nuclear pore complex and revealing specific design rules for manufacturing selective gels.

PIs: Katharina Ribbeck (co-lead), Bradley Olsen (co-lead), Patrick Doyle, Alan Grodzinsky, Paula Hammond, Niels Holten-Andersen, Jeremiah Johnson, and Gareth McKinley.

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. In recent work, the group reported order-of-magnitude thermal conductivity switching in $SrCoO_x$ upon modulation of oxygen and proton defect concentrations, giving rise to nanoscale "heat valve"–like behavior that can be implemented through gating in a liquid electrolyte. Extensive experimental characterization and ab initio modeling have isolated the phonon scattering effects from ionic defects and tensile strain due to lattice parameter changes, leading to a deeper understanding of the origins of this modulation as the system is switched among the three stable phases. Ionically controlled electrical and thermal conductivity was also tuned via gate voltage in WO_3 as a model system to demonstrate structural and electrochemical manipulation of charge and phonon transport. Oxygen content and hydrogen intercalation were used to vary lattice volume, revealing that volumetric strain plays a dominant role in governing phonon propagation through changes in bond stiffness and, hence, phonon velocity. Finally, the researchers have discovered oxygen vacancy-assisted hydroxide incorporation and protonic transport in GdO_x thin films that allow for solid-state catalytic atmospheric water splitting in ambient conditions and voltage-gated insertion/removal of protons in metal/metal-oxide heterostructures. Magneto-ionic switching of magnetization direction and magnetic anisotropy has been demonstrated, and modulation of magnetic damping and chiral exchange, as well as plasmonic switching and integrated charge storage in multifunctional structures, has recently been observed.

PIs: Caroline Ross (co-lead), Bilge Yildiz (co-lead), Geoffrey Beach, Gang Chen, Harry Tuller, and Krystyn Van Vliet.

Seed Projects

In addition to funding multi-investigator IRGs, MRSEC supports new faculty through seed programs. Current seed programs are described below.

Thin-Film Chromium Oxide Perovskites

This project explores correlated spin physics in a new family of chromium-based perovskites. Recent X-ray scattering experiments on $Sr_{2-x}La_xCrO_4$ Ruddlesden-Popper perovskite thin films revealed the coexistence of Néel and stripe magnetic orders, together with a hitherto-undetected electronic transition at lower temperatures. Characterization of a broader family of similar materials is under way to understand these phases. The PI for the project is Riccardo Comin (Physics).

Synthesis and Study of the Spin-Charge Interaction in Topological Semimetal/ Ferromagnet Heterostructures

The goal of this project is to understand spin transport in ferromagnet/topological-insulator heterostructures mediated by topologically protected electronic surface states. New experiments on bilayers of the topological Dirac semimetal Cd_3As_2 and ferromagnetic NiFe have provided evidence for spin pumping into the topological surface Fermi arc states of Cd_3As_2, suggesting that topological Dirac semimetals are promising materials for spin-pumping and spin-to-charge conversion applications. The project PI is Luqiao Liu (EECS).

Bottlebrush Hydrogels as Tunable Tissue Engineering Scaffolds

This seed aims to engineer hydrogel-based tissue scaffolds using bottlebrush polymers (BBPs) with unique design features. The required biocompatibility and biochemical functionality limit the choice of polymer building blocks, hindering property optimization. This project successfully synthesized a new BBP-based hydrogel with superior porosity and stiffness through coacervate formation of oppositely charged polymer brush ends that lead to network formation in solution. The project PI is Robert Macfarlane (DMSE).

Lithium Solid-State Memristor: Modulating Interfaces and Defects for Novel Li-Ionic Operated Memory and Computing Architectures

This project investigates Li-ion transport and defect kinetics in oxides to design memristor materials for synaptic computing. Recent progress includes the discovery and systematic study of non-volatile, non-filamentary bipolar resistive switching of lithium titanate compounds ($Li_{4+3x}Ti_5O_{12}$) as a function of lithiation degree. The work follows optimization of film growth using a strategy recently proposed by Jennifer Rupp (DMSE), the project's PI, to overcome lithium loss during deposition. Resistive switching characteristics reveal this material as a promising candidate for engineering neuromorphic computing elements.

Center for Integrated Quantum Materials

The Center for Integrated Quantum Materials (CIQM) is an NSF technology center led by Harvard University, with principal partners at MIT, Boston's Museum of Science, and Howard University. Now in its fifth year, the center focuses on discovering new quantum materials that will transform signal processing and computation. MIT's CIQM effort pulls together 10 PIs from the Department of Physics and EECS working in fields such as quantum materials, quantum electronics and photonics, and atomic scale networks. The new family of quantum materials being explored for their unusual electronic, optical, and magnetic properties includes graphene, hexagonal boron nitride, and molybdenum disulfide, among others. These materials have potential uses for sensing, information processing, and memory applications. Support is provided to seven graduate students, five postdoctoral associates, and a number of undergraduate students from MIT; also, graduate students are involved in exchange programs throughout the network of partner institutions. NSF has renewed the CIQM program for an additional five-year period.

Quantum Science Summer School

The NSF/Department of Energy (DOE) Quantum Science Summer School is a four-year program with the mission of training graduate students and postdocs in condensed matter physics, materials science, and disciplines of quantum science in engineering, chemistry, and related fields. NSF solely funded the program's first year, but it is expected that DOE will also contribute in future years, with total funding of $1 million.

The annual summer school focuses on key topics of interest in quantum science and their applications to new technologies in academic and industrial contexts. The goal is to provide training to participants in these subfields by experts in an intensive two-week format. The 2019 program focused on fundamental applications of quantum devices and was held in June at Pennsylvania State University. Program organizers included Assistant Professor Joseph Checkelsky (MIT), Associate Professor Natalia Drichko (Johns Hopkins University), Associate Professor Liang Fu (MIT), Assistant Professor Kyle Shen (Cornell University), and Associate Professor Jun Zhu (Pennsylvania State University). More than 150 students applied for the program, and 48 were accepted. The program covered students' expenses, including travel, housing, and meals.

Microphotonics Center

The Microphotonics Center (MPhC) was established in 1999 based on research on silicon photonic device integration and applications to support the demand for exponential growth in communication bandwidth that has enabled the information age. MPhC performs research and technology supply chain studies utilizing a technology working group (TWG) model. (These studies were originally incorporated in official releases of the MIT Communication Technology Roadmap.) The center's industrial advisory board commissions working groups that operate with the active participation of members and allied industrial partners from around the world. In addition to regular meetings of the MPhC board and TWGs, the center membership meets twice each year to review TWG progress and determine new initiatives.

In 2014, the MPhC Communication Technology Roadmap effort expanded through a funded program under the National Institute of Standards and Technology, working in collaboration with the International Electronics Manufacturing Initiative. The combined organizations broadened the topics of roadmap activity to include areas critical to manufacturing integrated electronic-photonic technologies. The result was the establishment of a new global industry roadmap (the Integrated Photonics System Roadmap), with new technology working groups created to address design, system integration, packaging and test requirements, and opportunities.

In addition, a federal Manufacturing USA award to the American Institute for Manufacturing Integrated Photonics (AIM Photonics), based in Rochester, NY, has provided continued support for MPhC manufacturing roadmap activities. TWGs have been established through project awards with AIM Photonics.

Along with its coordination of efforts with AIM Photonics, the center continues to maintain excellent and growing representation and participation from companies and organizations around the world. The center's roadmap activities address the larger supply chain challenges of the industry beyond silicon-based integrated photonics for network communications systems. New areas of focus for the center include the use of photonic technology for radio frequency systems, free space applications such as LIDAR (light detection and ranging), and consumer electronics.

Materials Systems Laboratory

The Materials Systems Laboratory (MSL) explores the economic and environmental consequences of choices of various materials systems and technologies with respect to resulting system changes. For example, the United Nations International Seabed Authority and MSL formed an important partnership in 2019 by developing simulation models of environmentally conscious deep-sea mining operations and the metallurgical facilities that obtain metals from recovered minerals. Using these models, MSL developed financial payment schemes that would incentivize commercial development while ensuring that all nations can share in the potential wealth the sea can offer.

MSL has worked with global mining companies to develop a first-of-its-kind screening tool that considers economic, geological, and technological factors to detect markets that are most likely to be fragile. Conversely, MSL has been working with Ford to identify supply chain vulnerability from the use of trace metals deep in the supply chain. Case work has focused on the materials surrounding vehicle electrification, including cobalt and copper, and the evolving patterns of materials demand in China and the developing world. MSL continues to be the global leader in modeling designed to understand this evolving personal transportation market.

MSL continues to be a co-leader in the MIT Concrete Sustainability Hub. The laboratory released a model that guides architects in their efforts to improve the environmental impact of new construction at the earliest stages of design, when changes can still be made, and also developed a new approach to allow state departments of transportation to manage their road networks at a lower cost and lower risk.

A new activity within MSL was initiated by Gregory Norris this year: the Sustainability and Health Initiative for Netpositive Enterprises program at MIT (SHINE@MIT). SHINE@MIT is developing methods that characterize both negative and positive environmental impacts of activities of firms as well as life-cycle assessment methods that focus on firms instead of products. The program is associated with ongoing parallel activities at Harvard, where the focus is on employee health evaluations. SHINE@MIT is supported in part through an industrial consortium.

Manufacturing USA Institutes

MRL has significantly increased its support of MIT faculty engagement with the Manufacturing USA Institutes. In addition to providing support for the Lightweight Innovations for Tomorrow Manufacturing Innovation Institute and the American Institute for Manufacturing Integrated Photonics, MRL is supporting faculty engagement with the newly established Advanced Functional Fabrics of America (AFFOA) and Reducing Embodied Energy and Decreasing Emissions Institute (REMADE). These institutes offer challenging new avenues of government-industry-academia interactions for technology transfer combined with education and workforce development programs.

AIM Photonics

AIM Photonics, established under an Integrated Photonics Institute for Manufacturing Innovation award on July 27, 2015, is funded through a five-year, $110 million federal investment combined with a $500 million industry-state cost share commitment. The public-private partnership is designed to help strengthen US-based high-tech manufacturing. AIM Photonics brings government, industry, and academia together to advance domestic capabilities in integrated photonic technology. The lead institution in this partnership is the University of New York Polytechnic Institute. The AIM Photonics executive management team includes Associate Professor Michael Watts as chief technology officer and Professor Lionel Kimerling as education, workforce development, and roadmap executive. AIM Photonics is now in its fourth year of operation. MRL supports Professor Kimerling as the lead PI for MIT with AIM Photonics.

The AIM Photonics Academy, based at MIT, was established under the leadership of Professor Kimerling as the organization leading the development of education, workforce development, and roadmap content and services addressing manufacturing technology issues for the integrated photonics industry. The academy is leveraging online education platforms such as MITx and TedEd to extend its educational reach to industry and the general public. The academy leadership team includes participating members from the University of Rochester, the Rochester Institute of Technology, Boston University, and the University of Arizona. The AIM Academy's execution of its responsibilities is closely coordinated with local and state organizations (e.g., the Massachusetts Department of Housing and Economic Development and the Massachusetts Technology Collaborative) in support of education and workforce development programs and tools for photonics at universities and community college consortia.

In fall 2017 the AIM Photonics Academy, together with the state of Massachusetts and regional community colleges, began a partnership program to establish several Laboratory for Education and Application Prototypes (LEAP) initiatives that will enable companies to train their workforces in new technologies associated with integrated photonics. The MIT LEAP site will focus on manufacturing practices and technician training and certification. The AIM Academy will be working with the other LEAP sites to create a coordinated set of capabilities that will support the region's growing industry.

As the AIM Photonics Academy has developed broad and innovative activities in education and workforce development, it has become clear that its support would be more appropriately managed through an academic unit. Administration of AIM Photonics Academy activities will be moved to the Department of Materials Science and Engineering in FY2020. AIM Photonics research and road mapping activities will remain in MRL.

Professor Duane Boning leads the second major program supported by AIM Photonics at MIT. Design for Manufacturability Methods for Photonic Systems is in its third year. The objective of this program is to develop methods for photonic systems that will evaluate and help improve the understanding of process variability using processes that fabricate components associated with the design kits developed under AIM. The program also looks specifically at silicon-based photonics components such as waveguides, ring resonators, and other elements used for routing, modulating, and detecting photonic information in integrated circuits.

Lightweight Innovations for Tomorrow

MSL continued to play a key role in the Lightweight Innovations for Tomorrow (LIFT) Manufacturing Innovation Institute this past year. LIFT provides a national focus on expanding US competitiveness and innovation by facilitating the transition of advanced lightweight and modern metals manufacturing capabilities and new technologies to the industrial base. Federal support is provided through the Office of Naval Research. Previous LIFT chief technology officer Alan Taub has stepped down and is now a senior consultant. Principal research scientist Randolph Kirchain is leading the MIT component of the LIFT activity, which focuses on ways to ensure that modeling and data science can continue to improve the competitiveness of US-based shipbuilding, auto manufacturing, and aerospace as well as the light metals supply chains that support these industries. Although federal support of LIFT ended this fiscal year, the institute will continue with support from industrial sponsors and individual government agencies. This will involve reorganization of LIFT activities and priorities.

Reducing Embodied Energy and Decreasing Emissions Institute

The Reducing Embodied Energy and Decreasing Emissions Institute is one of the latest program awards under the Manufacturing Innovation Institutes initiative supported by the US government. The award for the REMADE proposal was announced in January 2017. REMADE is led by the Sustainable Manufacturing Alliance, based at the Rochester Institute of Technology. It will leverage federal funding of $70 million over five years and is matched by an additional $70 million in private cost shares from industry and other organizations. The institute will focus on driving down the costs of technologies essential to reuse, recycle, and remanufacture materials such as metals, fibers, polymers, and electronic waste, with the objective of achieving a 50% improvement in overall energy efficiency by 2027. REMADE has organized its activities around topics such as remanufacturing and end-of-life reuse, recycling and recovery, and systems analysis and integration.

MRL is supporting Professor Elsa Olivetti, the lead PI for MIT with REMADE, and is coordinating MIT faculty proposals and administration of specific program award activities. Professor Olivetti is actively working with the REMADE organization and with fellow professors at MIT, collaborators at other institutions, and industry to respond to calls for proposals. Her proposal focusing on identifying strategies to maximize the benefit of fiber recovery through systems quantification has been accepted pending completion of the associated agreement. The project, anticipated to begin in the fall, will create a dynamic and probabilistic analysis and simulation model that leverages existing data and tools to provide a comprehensive, statistically robust estimate of fiber recovery technologies and scenarios.

Advanced Functional Fabrics of America

MIT was the lead institution for a successful proposal to create the AFFOA Manufacturing Innovation Institute, which was launched in April 2016. The AFFOA program functions through a partnership with the Department of Defense (DOD), 32 universities, 16 industry members, 72 manufacturing entities, and 26 startup incubators spread across 28 states. AFFOA's mission is to enable the transformation of traditional fibers, yarns, and textiles into highly sophisticated integrated and networked devices and systems.

AFFOA is developing fibers in which chip and power technologies are incorporated into the material itself to deliver fibers with increasing functionality. AFFOA works with industry to create fabrics that can store and convert energy, regulate temperature, monitor health, and change color. The partnership aims to create new markets for advanced fabrics wherein these materials provide a platform for delivering high-value-added services.

The AFFOA headquarters and research facility opened in Cambridge on June 19, 2017. The facility includes a fabric discovery center that provides end-to-end prototyping from fiber design to system integration of new textile-based products. It also includes a startup incubation space for companies spun out from MIT and other partners that are innovating advanced fabrics and fibers for applications ranging from apparel and consumer electronics to automotive and medical devices.

The MIT component of the AFFOA program is led by Professor Gregory Rutledge of ChemE and is administered through MRL. Professor Skylar Tibbits was the first to receive an award for his "Shape-shifting Climate-Adaptive Garments" proposal. The project focuses on the development and use of temperature-adaptive materials to create "smart" garments that can increase performance and breathability through tunable compression and porosity based on the design of fibers and associated fabrics. Applications of the technology are suitable for the athletic leisure and performance apparel markets.

International Programs

Singapore-MIT Alliance for Research and Technology Low Energy Electronic Systems

The Singapore-MIT Alliance for Research and Technology (SMART) is directed by Professor Eugene A. Fitzgerald, who is also the lead principal investigator for the SMART Low Energy Electronic Systems (LEES) interdisciplinary research group. The SMART LEES, managed through MRL, is in the third year of a five-year phase 2 program with a budgeted research volume of approximately $1.3 million per year for the first four years and a ramp-down budget of $650,000 for the fifth and final year. The Singapore-based volume is approximately three times greater.

The SMART program involves seven MIT faculty and an MIT senior research scientist as well as their students and postdocs based at MIT. Eleven faculty from the Nanyang Technological University (NTU) and the National University of Singapore (NUS) are also involved in collaborative research. Twenty-four MIT staff and postdocs are now supported in Singapore for research based there.

The goal of the LEES program is to demonstrate practical approaches to integration of compound semiconductor devices with conventional Si-based integrated circuits. Relative to silicon, compound semiconductor devices have superior properties for use in photonic and power devices. These devices include solid-state lasers, light-emitting diodes, and high-power, high-electron mobility transistors. Mature silicon integrated circuit technology provides capabilities for high-performance computation and data analysis. Integration of compound semiconductor devices with silicon circuits will enable technologies for high-speed communication within and between circuits, advanced displays and lighting made "smart" through integration with silicon-based control circuits, improved wireless communication technologies, and on-chip power management for low-power circuits to be used in mobile technologies.

The LEES program has created an environment that encourages experts in materials processing, device and circuit design, and systems architecture to work in close concert to develop fundamentally new integrated circuit technologies that will enable new applications. To implement these new technologies, LEES has developed a 200-mm wafer processing facility in Singapore that includes two state-of-the-art metal organic chemical vapor deposition systems as well as other facilities with capabilities for conventional chemical vapor deposition, wafer bonding, chemical mechanical polishing, and materials and device characterization. Coupled with other facilities available through collaborations with NTU and NUS, full capabilities for III-V device processing on silicon substrates have been developed. Collaborations with two semiconductor integrated circuit foundries have also been established, and wafers can pass from these foundries to the LEES facility and then back into the foundries for different stages of circuit processing. Through these collaborations, LEES compound semiconductor devices have been integrated with Si integrated circuits to provide new functionalities using the existing manufacturing infrastructure. This will enable rapid adoption of processing and design methodologies developed in LEES in the electronics industry.

SMART Critical Analytics for Manufacturing Personalized Medicine

SMART and A*STAR Institutes, with support from the National Research Foundation (NRF), have launched SMART Critical Analytics for Manufacturing Personalized Medicine (CAMP), a national initiative in Singapore for cell manufacturing. CAMP is a new interdisciplinary research group that will focus on ways to produce living cells as medicine delivered to humans, leading to improved health outcomes. NRF will support this multimillion-dollar multi-year project, which will bring together 35 MIT and Singapore investigators. They will be recruited from researchers working in SMART and Singapore institutes including A*STAR, the KK Women's and Children's Hospital, the National University Hospital, and local universities. CAMP will be led by Krystyn Van Vliet from MIT and Professor Hanry Yu of NUS and A*STAR and will involve 15 MIT Faculty from multiple departments.

Skoltech Center for Electrochemical Energy Storage

The Center for Electrochemical Energy Storage (CEES) continued into its sixth and final year in 2019. CEES is one of nine centers for research, education, and innovation (CREIs) that provide support for research and teaching at the Skolkovo Institute of Science and Technology (Skoltech). Skoltech was founded through the MIT Skoltech Initiative in 2011. Each of the original CREIs was based on collaborations among Skoltech, a Russian university (Moscow State University in the case of CEES), and an international university (MIT in the case of CEES). CEES is the only remaining center in which MIT plays a lead role.

The CEES team is highly interdisciplinary and involves faculty from the MIT Departments of Mechanical Engineering (MechE), ChemE, DMSE, and Chemistry as well as faculty from the Departments of Physics and Chemistry at Moscow State University; five Skoltech faculty members, including the center director, are also involved.

Research in CEES is focused on three thrusts targeting technologies that will replace current Li-ion battery technology: (1) advanced metal-ion batteries, (2) rechargeable metal-air batteries, and (3) fuel and electrolysis cells.

In the past year, thrust 1 research centered on investigation of metal salts based on metal metaphosphate complexes as active materials for flow batteries, development of electronically conductive aqueous carbon suspensions for low-cost electrolyzers, and development of new electrode materials for use in Li-ion thin-film batteries integrated with Si circuits and devices for autonomous microsystems. Work on low-cost electrolysis led to new research activity in energy-efficient electrochemical routes for cement production. This work resulted in several patent applications.

Thrust 2 research continued development of rechargeable metal-air batteries, primarily Li-air batteries with potential gravimetric energy densities that are two to four times those of optimized Li-ion batteries. Specific activities focused on improved understanding of solvation mechanisms and pathways as well as catalysis of redox processes at electrode surfaces as a path to discovery of redox mediators that will improve cycling efficiency. Theoretical and experimental studies of the effects of surface structure and stoichiometry on catalytic abilities also played a key role in thrust 3.

Thrust 3 research centered on the discovery of new materials for solid oxide fuel cells (SOFCs) and solid oxide electrolysis cells, including perovskite solid oxide electrolytes. Ruddlesden-Popper-type cuprates and nickelates were also investigated as model SOFC electrode materials to gain a deeper understanding of the rate-limiting mechanisms behind oxygen exchange rates and thermochemical stability as they relate to the capacity to operate SOFCs at reduced temperatures.

As a follow-up to the successful MIT Skoltech CREI program, which will end in 2019, Skoltech and MIT have developed next-generation research programs supporting one-on-one collaborations between PIs at the two institutions. Within MRL, Professor Nuh Gedik (Department of Physics) has established a program on investigation of high-temperature superconductors and other complex quantum materials, while Professor Yet-Ming Chiang (DMSE) has initiated a program on exploration of electrode materials for potassium ion batteries.

Industry Interactions

MRL continues to support faculty research efforts with industry collaboration over a wide range of materials- and science-based applications, from metallurgical coatings for strength and corrosion resistance to integrated photonics, solar cells, and batteries. MRL supports many ongoing research programs with faculty, including Professor Lionel Kimerling's programs with 3M, AIM Photonics, Global Foundries, Microsoft, and NTT Electronics; Randy Kirchain's research with Ford and Rio Tinto; Professor Antoine Allanore's programs with Advanced Potash, Apple, and Novelis; Professor Elsa Olivetti's program with Advanced Micro Devices; Associate Professor Cem Tasan's research with ATI, Gillette, Metalsa, and Yamaha; Senior Research Scientist Jurgen Michel's programs with the Advanced Research Projects Agency-Energy (ARPA-E) and Futurewei; and Professor Christopher Schuh's research with Ormco and Mitsubishi Materials.

MRL also supports faculty with the establishment and operation of consortium research programs with industry. Ongoing programs for 2018 and 2019 include the Materials Systems Laboratory, SHINE@MIT, and the Microphotonics Center.

MRL partners with Industrial Liaison Program (ILP) officers in support of company inquiries and members' interests in faculty research. MRL support includes coordination with ILP officers and faculty for meetings as well as technical briefings and seminars offered by the MRL director and associate director. Significant company meetings coordinated with ILP officers throughout the year were held for senior executives and researchers from JXTG Holding, Nippon Electric Glass, PTT, and SOCAR-AQS. MRL also supports other major events sponsored by ILP, including its research and development conferences in Japan and at MIT.

In fall 2018, speakers participating in the ILP research and development conference included Professors Carl V. Thompson, Rafael Jaramillo, Juejun (JJ) Hu, and Ju Li. Some of the topics covered were new methodologies in materials research for accelerated innovation; chalcogenide active materials for photonics, photovoltaics, and chemical sensing; and machine-learning-enhanced chip-scale spectrometers for chemical sensing. We expect to continue these collaborations in the future.

Corporate Innovation Workshops

MRL held two corporate innovation workshops this year. These newly established events are aimed at identifying and optimizing current modes of industry-academic engagements and developing new modes of interaction focusing on engagement in the corporate innovation process. MRL will serve as a testbed for ideas emerging from these activities. The workshops were developed in collaboration with the National Academies of Sciences, Engineering, and Medicine and involved participants from the BASF Corporation, Danfoss A/S, the Dow Chemical Corporation, GC Innovation America, General Electric, General Motors, Henkel Adhesive Technologies, Keysight Technologies, the Lockheed Martin Corporation, M Ventures, Matheson Tri-Gas, Pellion Technologies, Philips HealthWorks, SABIC, Saint-Gobain, Samsung, The Boeing Company, The Cantabia Group, TOTAL, United Technologies, the wTe Corporation, and the Zapata Corporation. Three working groups have been formed to focus on technology scouting, talent, and partnerships. These groups will compile reports, and action plans will be developed at a meeting in the fall.

Industry Collegium

The MRL Industry Collegium membership program was updated and relaunched in FY2019. New benefits include hosting of a staff member for short- or long-term visits on campus, discounted fees for access to and use of the MRL materials characterization shared user facilities, a greater emphasis on engagement between company members and MIT students, and discounted fees for participation in MRL events.

The Industry Collegium consists of six companies that provide direct financial support for MRL's discretionary activities through annual membership donations. Representatives from these companies work with MRL throughout the year to identify opportunities for collaboration and participate in the laboratory's annual Materials Day symposium and poster session. Current collegium members are as follows: Applied Materials, BASF, Dyson, Ishikawa-Heavy Industries, Merck KGaA, and Raytheon.

New Programs with Industry

New industry-supported research programs with MRL faculty initiated in FY2019 include Anu Agarwal's research with Radiation Monitoring Devices, Professor Antoine Allanore's research with OCP, Professor Rafael Jarmillo's research with Draper Laboratory, Randolph Kirchain's research with Multi-Source, Associate Professor Jennifer Rupp's research with NGK Spark Plug and the Samsung Advanced Institute of Technology, and Associate Professor Cem Tasan's research with Allegheny Technologies and Mitsubishi Materials. Topics covered by the new programs include investigation of chalcogenide glasses for optical-based communication and sensing, economic analyses of materials processing operations, and processing and characterization of metals and metal alloys.

MRSEC Shared Experimental Facilities

Our shared experimental facilities (SEFs) are a critically important resource to the MRSEC program and to the MIT community, as well as a number of outside academic and industrial organizations. Currently there are four major facilities, Materials Analysis, Electron Microscopy, X-ray Diffraction, and Nano Materials, staffed by a team of highly motivated professionals. Over the past year, more than 1,000 different individuals (representing 21 MIT departments, labs, and centers; 10 outside academic units; and 13 outside commercial units) utilized these facilities.

Beyond the special role the SEFs play in the training and education of MIT students, they are also an important part of the MRSEC 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. Also, during January 2019, five technical courses were offered by the SEF technical staff to the MIT community as part of Independent Activities Period (IAP). Finally, the SEFs are included in visits to MRSEC by various groups of middle and high school students.

During FY2019, the new MRSEC In-situ SEM Characterization Facility was established as part of the Electron Microscopy SEF. This new scanning electron microscopy (SEM) in situ analysis testing user facility was created with funding from Cem Tasan's group, the Lord Foundation, DMSE, the Office of the Vice President for Research (VPR), and the School of Engineering, along with MRSEC discretionary funds. The facility is able to carry out in situ SEM uniaxial tension, compression, bending, nanoindentation, and electrical property characterization tests as well as additional novel in situ SEM experiments.

The MIT MRSEC also continues to be an active participant in the NSF Materials Research Facilities Network. Participation in this network enables access to our facilities by researchers from other universities, particularly those who have limited research tools and are affiliated with minority-serving institutions. A process has been established that involves the submission of a short proposal outlining the analysis to be done and how the results will impact the proposer's research program and, if relevant, educational activities. During the past year, Olufolasade Atoyebi from Howard University visited MIT to use our Electron Microscopy SEF, samples were prepared and analyzed in our X-ray lab for Louisiana State University, and Professor Kimberly Stiglitz from Roxbury Community College brought students from her research science course to our X-ray SEF.

The Electron Microscopy SEF's sample preparation room, shared common area, hallways, and entry area are being upgraded with funding from MRL, DMSE, and VPR. These much-needed upgrades will provide new case work areas for the sample preparation room, new floors and lighting for the hallways, and a new common area for collaborations and presentations. Also, as part of the renovation process, two new microscopy suites are being created for Professor Frances Ross. These suites will have specialized microscopes that will become part of the electron microscopy facility.

Interactions with MIT.nano

Since the formation of MRL, we have worked closely with MIT.nano to coordinate and plan collaborative activities including use of research areas based on equipment performance requirements. MRL is represented on the MIT.nano leadership team by Carl V. Thompson and on the Tool Committee Subgroup on Metrology by Geoffrey Beach. Vladimir Bulović, director of MIT.nano, serves on the MRL Internal Advisory Board. Bulović, Thompson, and Beach engage in ongoing discussions focused on identification of other modes and mechanisms of collaboration that support the missions of both organizations.

MIT.nano offers unique capabilities in terms of electromagnetic and vibration isolation, providing enhanced performance to materials characterization systems. Some of the MRL/MRSEC SEFs may be relocated into MIT.nano. If this occurs, the technical staff responsible for MIT.nano facilities will report to the MIT.nano management structure. MRL will be consulted regarding related staff hiring and evaluation of fiscal management. The SEFs operating within Building 13 will continue to be managed by MRL. We anticipate that the facilities in Buildings 12 and 13 will be managed and billed in such a way that their different management structures will not be apparent to internal or external users.

Over time, the MRL tool set will evolve to focus more on capabilities that enable materials experimentation such as in situ and real-time imaging and analysis of evolving structural and chemical properties of materials. This strategy will complement MIT.nano's focus on materials characterization capabilities through Metrology.nano.

Outreach

MRL does not limit its educational outreach to the MIT community. We have 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. MRSEC has 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 outreach programs are managed by a full-time education officer who works closely with a faculty education program leader, the center director, the associate and assistant directors, and other MRL staff.

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

Materials Research Experience for Teachers

For the past 20 years, MRSEC has operated a successful MRET program. This program brings high school and middle school teachers to MIT to participate in MRSEC 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. Three teachers participated in the 2018 summer program.

Community College Program

For the past several years, the MRL MRSEC has collaborated with Roxbury Community College and Bunker Hill Community College, 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. During summer 2018, six students participated in the program.

Partnership with Universidad Metropolitana

In 2008, we formed a collaboration with 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). Arratia refers students to the 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, 23 students have participated in the program, and an additional two students spent two weeks at MIT working with graduate students to learn to use research instruments in the SEFs. Of the 23 students who have been involved in the program, four are still completing their undergraduate studies. Another eight have proceeded to graduate school, one of whom has completed her PhD. Seven others have completed their bachelor's degrees and are employed: five as engineers, one in manufacturing, and one as a technology consultant. 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.

Science Teacher Enrichment Program

The MRL MRSEC offered its Science Teacher Enrichment Program (STEP) for the 18th time in the summer of 2018. 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 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 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 (WTP). 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 2018 STEP.

A companion effort to STEP is MRSEC's collaboration in the Women's Technology Program 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. MRSEC invites the WTP participants to join the lab portion of STEP to gain hands-on engineering experience. WTP alumni report that this motor-building lab is an exciting part of the program. MRSEC continued to support WTP by providing the curriculum and supplies for this part of the program in 2018 and will again do so in 2019.

Science and Engineering Program for Middle School Students

The MRSEC program has operated a science and engineering program for seventh- and eighth-grade students from two Cambridge public schools for the past 27 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 2018, 13 seventh- and eighth-grade students attended with their science teachers. The students participated in hands-on activities presented by faculty, staff, graduate students, and undergraduates. The 2018 program included classes on ultraviolet light, simple DC motors, electric circuitry, polymers, glass blowing, metal casting, and solar cells.

MRSEC Diversity

MRSEC's diversity plan consists of three integrated strategies designed to increase participation by women and members of traditionally underrepresented groups in the center's research and education programs: (1) increasing diversity among participants in MRSEC's existing programs, (2) developing and refining dedicated programs that target underrepresented groups, and (3) collaborating with other offices and departments at MIT and beyond to enhance diversity on campus and in science and engineering fields. The table below details participation in various MRSEC programs.

MRSEC Participants, 2018–2019

	Total	Females	Minorities
Science and Engineering Program for Middle School Students	**13**	6	7
Women's Technology Program	**40**	40	0
Materials Research Experience for Teachers	**3**	3	0
Science Teacher Enrichment Program	**3**	1	0
Research Experiences for Undergraduates*	**12**	7	3
Community College Program	**6**	1	4
Undergraduate Research Opportunities Program**	**9**	6	0
Graduate students**	**37**	11	0
Postdoctoral associates**	**17**	2	1
Faculty	**27**	8	2
Total	**167**	85	17

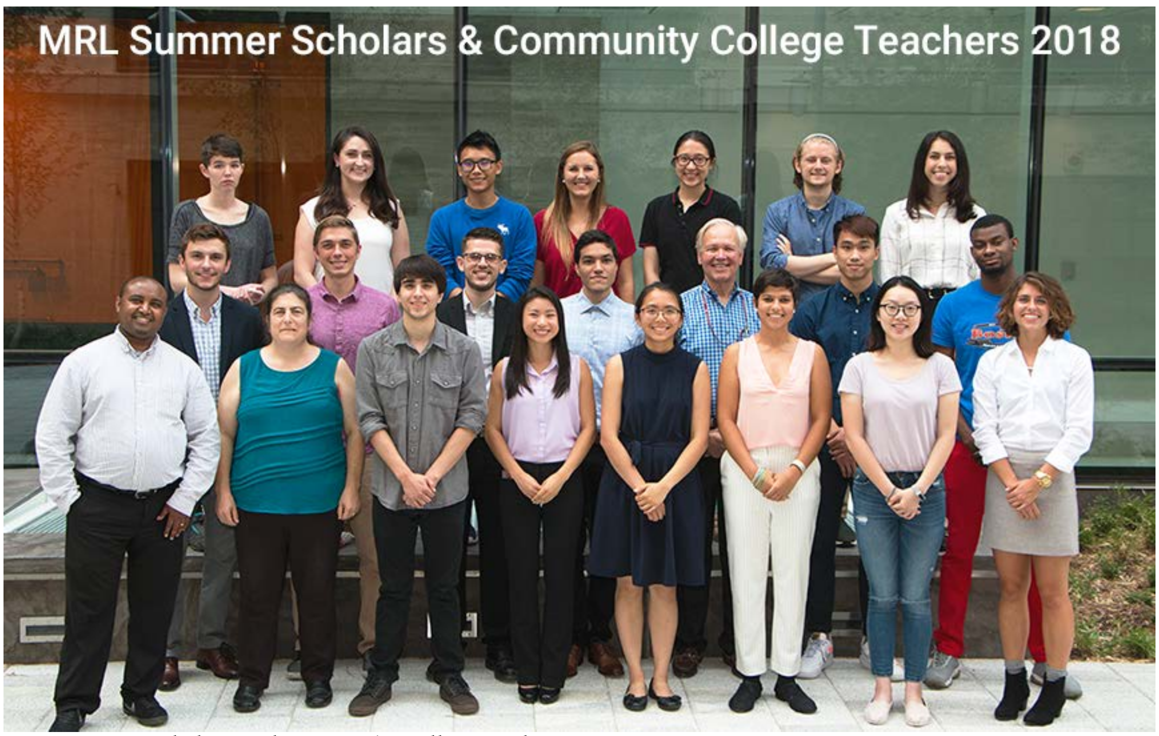
*Includes six community college students and one other student paid with non-MRSEC funds.

**Includes individuals who were paid directly through the grant as well as those who worked on MRSEC research for academic credit or were supported with other funds.

Summer Research Internship Program

For 35 years, the MRL MRSEC has sponsored a summer internship program for promising undergraduate researchers from other colleges and universities nationwide. The MRL summer internship is an NSF Research Experiences for Undergraduates program. The program brings the best science and engineering students in the country to MIT for graduate-level materials research in laboratories of participating faculty. The program culminates in a poster session held in the lobby of Building 13, where students present their research to the MIT community.

This year's eight-week program ran from June 16 to August 10 and involved 15 faculty and 10 students from schools including the University of California, Los Angeles; Case Western Reserve University; Dartmouth College; Northwestern University; Hunter College; the University of Massachusetts Amherst; the University of Puerto Rico, Mayaguez; Ana G. Mendez University, Gurabo (Puerto Rico); the University of Pittsburgh; and the University of Washington.



2018 summer scholars and community college teachers.

Materials Day

Sharing knowledge and insight with others in the materials science and engineering field can lead to new ideas, collaborations, and breakthroughs. Once a year, the materials community is invited to Materials Day, a celebration to recognize and honor the many important accomplishments and achievements of the past year and to talk about the future.

Held in the fall, Materials Day is a daylong symposium on a featured topic related to materials science and processing, followed by a graduate student/postdoctoral associate poster session. The Materials Day 2018 symposium focused on materials research at the nanoscale. Seven presentations were offered over the course of the day, by both faculty and industry professionals, drawing a crowd of more than 200 attendees.

Invited speakers (and the titles of their talks) were as follows: Matthew Kulzick of the BP Amoco Chemical Company ("Application of Advanced Microscopy to Industrial Problems: New Tools Give New Insights"), Professor Frances M. Ross of MIT ("Imaging and Controlling Nanoscale Crystal Growth in the Transmission Electron Microscope"), Professor Sylvija Gradecak of MIT ("An Electron Walks Into a Bar…Electron Microscopy Beyond Imaging"), David E. Moncton of MIT ("Compact Synchrotron Radiation Sources Enabling Advanced X-ray Imaging and Diffraction Methods in a Laboratory Setting"), Associate Professor Cem Tasan of MIT ("Nanoscale Insights for Macroscale Solutions: Exploring Novel Damage-resistance Mechanisms in Metals"), James LeBeau of North Carolina State University ("Accelerating the Pace of Materials Characterization at the Atomic Scale: From Machine Learning to Novel Detectors"), and Professor Karl Berggren of MIT ("Using Quantum Mechanics to Hack the Electron Microscope").

The poster session that followed panel presentations and discussions included over 75 posters presented by graduate students and postdoctoral associates from departments such as ChemE, Chemistry, Civil and Environmental Engineering, EECS, Aeronautics and Astronautics, DMSE, MechE, Nuclear Science and Engineering, BE, and Physics. The posters were judged by a panel of representatives from industry as well as members of the MRL advisory board. Winners received award certificates and $500 prizes. Poster session winners were as follows:

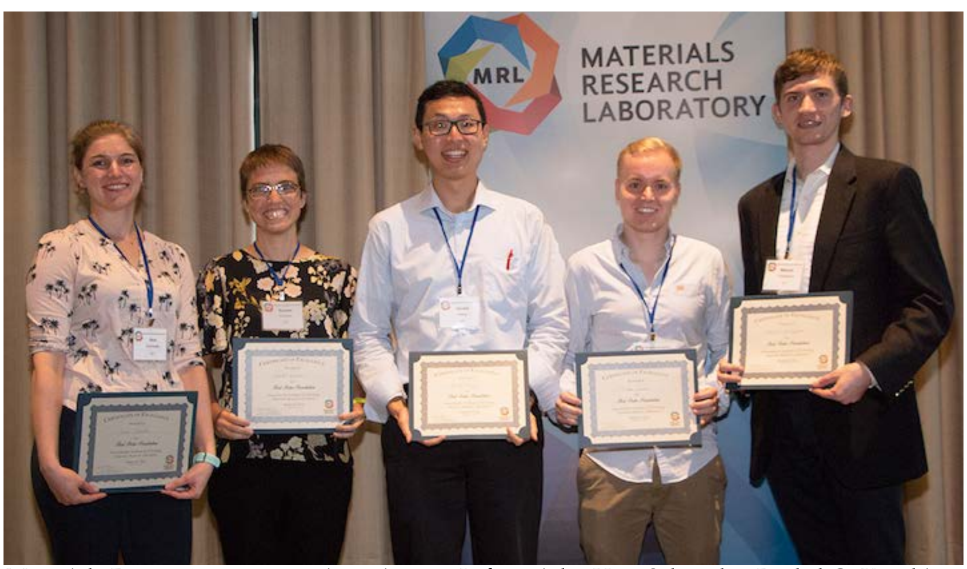
Vera Schroeder ("Translating Catalysis to Chemiresistive Sensing")

Rachel C. Kurchin ("Toward Quantitative Metrics for Defect Tolerance in Semiconductors")

Gerald J. Wang ("A Day in the Life of a Nanoscale Plumber")

Philipp Simons ("All-Solid-State Glucose Fuel Cell for Energy Harvesting in the Human Body")

Mikhail Y. Shalaginov ("Optical Phase-chance Materials for Reconfigurable Metasurfaces")



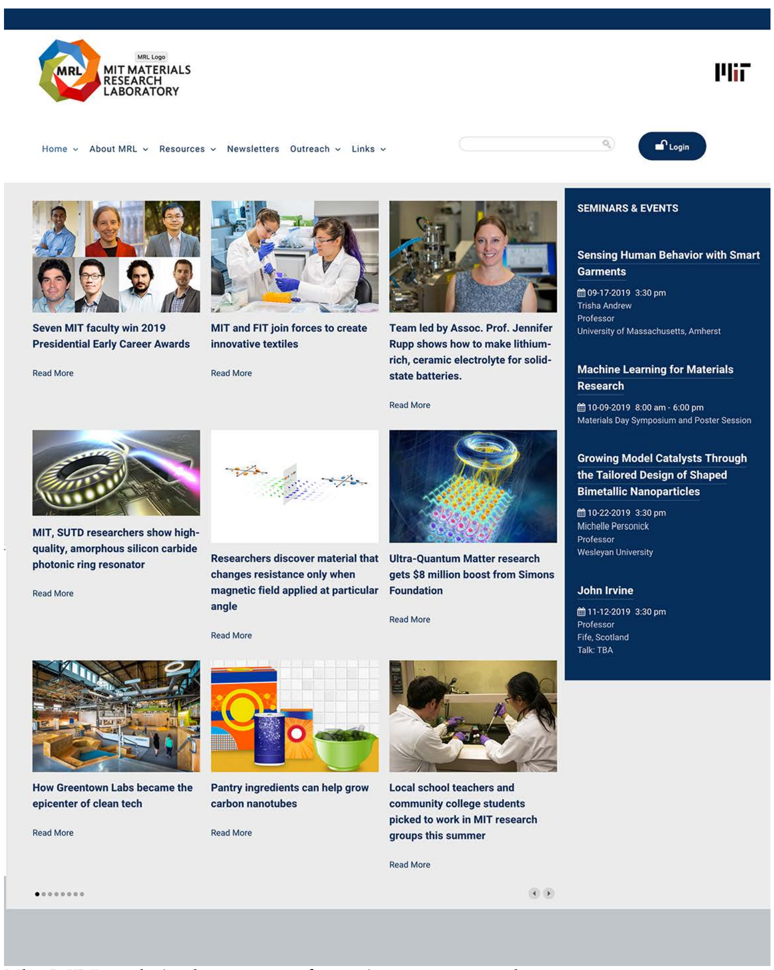
Materials Day 2018 poster session winners. Left to right: Vera Schroeder, Rachel C. Kurchin, Gerald J. Wang, Philipp Simons, and Mikhail Y. Shalaginov.

Communications

MRL works with centers and departments across MIT to effectively communicate research, faculty, graduate student, and postdoc accomplishments through a common storytelling lens. By sharing the groundbreaking work our postdocs and faculty do every day, across a wide variety of media and through a variety of channels, we create compelling stories. Our goal is to deliver a steady cadence of content through our website and through social media.

The website is updated daily and highlights news stories generated for our e-newsletter, as well as related news from the MIT News Office. This year 40 original articles were written and photographed for the e-newsletter, and 19 of those articles were picked up by the MIT News Office for use on its own website. Other departments within the Institute as well as organizations outside MIT also picked up our articles. In addition, we produced six videos.

Rebranding Building 13 with the MRL logo was of particular importance this year. New floor directories as well as way-finding signs were installed on every floor of the building. Also, a new conference room booking calendar system was created and launched, allowing various staff members to have access to book the building's conference rooms.



The MRL website homepage, featuring a news and announcements segment that can be sorted by topic.

Promotions and Selected Honors and Awards

Professor Antoine Allanore (DMSE) became a tenured faculty member and won the 2019 Elsevier Atlas Award. He also received a third-place prize for best conference proceedings manuscript at the TMS Annual Meeting and Exhibition in March.

Professor Dimitri Antoniadis (EECS) was elected to the American Academy of Arts and Sciences in April.

Professor Paula Hammond (ChemE) received the 2019 Margaret H. Rousseau Pioneer Award for Lifetime Achievement by a Woman Chemical Engineer from the American Institute of Chemical Engineers (AIChE). This award is presented to a woman member of AIChE who has made significant contributions to chemical engineering research or practice over the course of her career.

Professor Harry Tuller (DMSE) received in May the Thomas Egleston Medal for Distinguished Engineering Achievement from Columbia University. The medal recognizes distinguished achievement in engineering or applied science. The recipient must have significantly advanced their engineering field or the management of engineering activities.

Ellen Swallow Richards Professor Frances Ross (DMSE) became a tenured professor. Ross performs research on nanostructures using transmission electron microscopes that allow researchers to see, in real time, how structures form and develop in response to changes in temperature, environment, and other variables. Understanding crystal growth at the nanoscale is helpful in creating precisely controlled materials for applications in microelectronics and energy conversion and storage.

Cem Tasan was promoted to associate professor. Tasan explores the boundaries of physical metallurgy, solid mechanics, and in situ microscopy in order to provide game-changing materials solutions to environmental challenges.

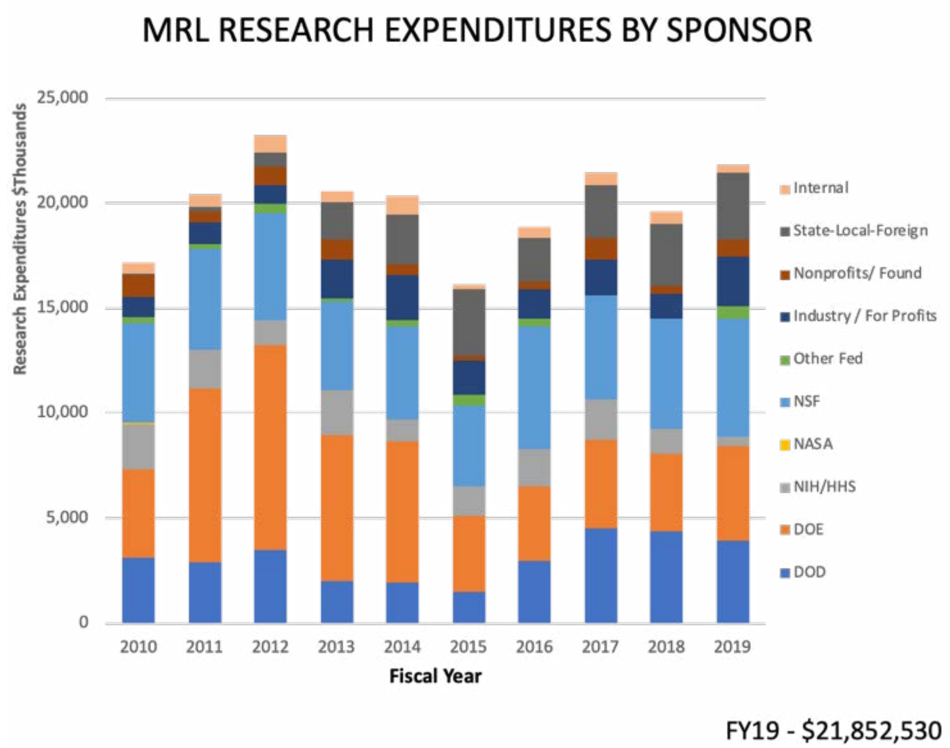
Jennifer Rupp was also promoted to associate professor. Her research focuses on solid-state material design and tuning of structure-property relations for novel energy and information devices and operation schemes.

Research Volume

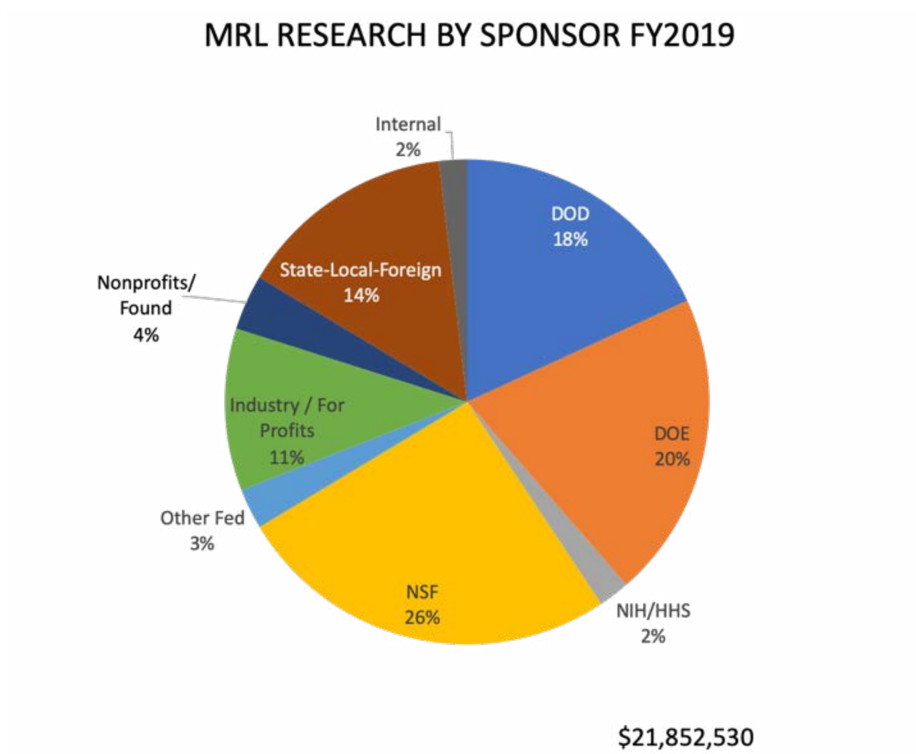
Total expenditures under MRL were $23.3 million in FY2019. Research expenditures from sponsored programs totaled $21.8 million, an increase of 11.6% over FY2018.

Major program expenditures included the American Institute for Manufacturing Integrated Photonics (in collaboration with the State University of New York Research Foundation), supported by DOD and led by Professor Lionel Kimerling and five co-PIs; the NSF-supported Center for Integrated Quantum Materials, in collaboration with Harvard University and led by Professor Raymond Ashoori and 11 co-PIs; the Low Energy Electronic Systems program within SMART, led by Professor Gene Fitzgerald and eight co-PIs; the Skoltech Center for Electrochemical Energy Storage, led by Professor Carl V. Thompson and five co-PIs; the Chemomechanics of Far-From-Equilibrium Interfaces program, supported by DOE and led by Professor Krystyn

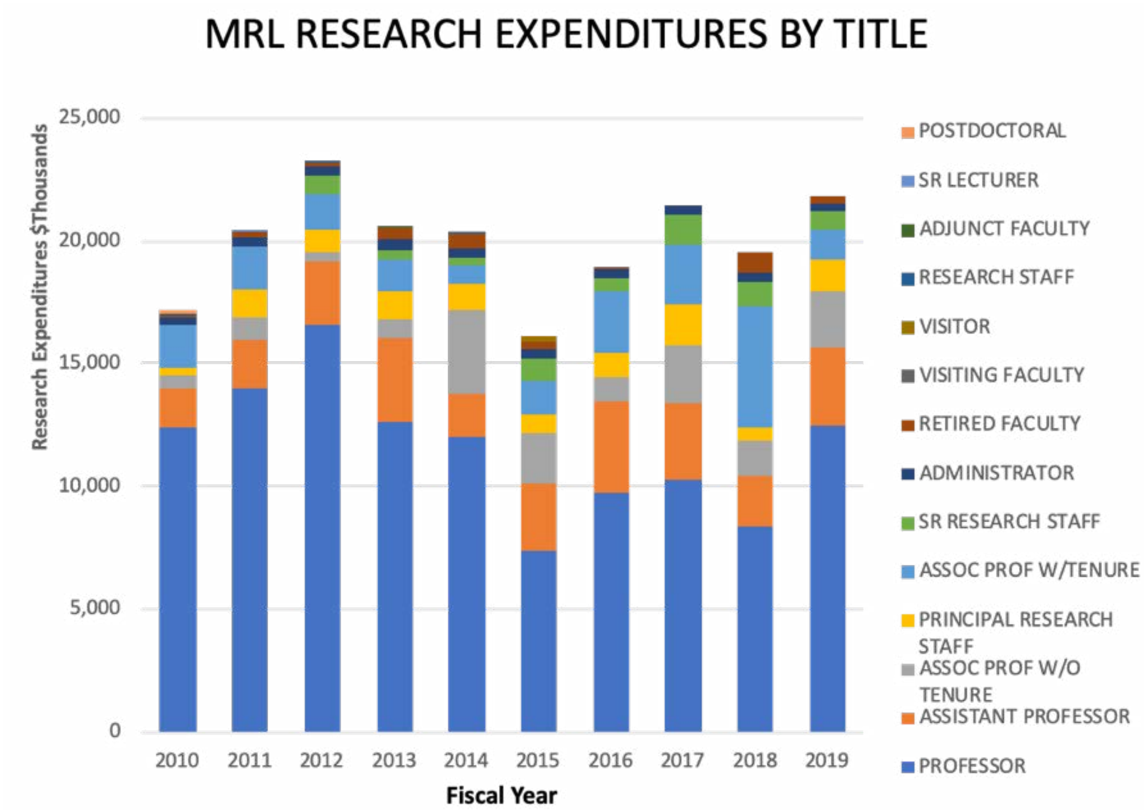
Van Vliet and five co-PIs; the Shape Shifting Climate Adapting Garments program, supported by AFFOA and led by Associate Professor Skylar Tibbits; and the Integrated Micro-Optical Concentrator program, supported by ARPA-E and led by Senior Research Associate Jurgen Michel and four co-PIs.



MRL sponsored research volume, FY2010–FY2019 (includes historical research expenditures for the NSF MRSEC program, formerly administered by CMSE).



MRL major sponsors, FY2019.



MRL research expenditures, by title, FY2019.

Overview and Outlook

The MIT materials research community includes over 200 faculty and other principal investigators from all departments in the Schools of Science and Engineering as well as from the School of Architecture and Planning. This interdisciplinary community exercises global scientific and technological leadership and has been the source of many new technology enterprises. The Materials Research Laboratory serves this community through activities that support and enable research, events that support community building within MIT, and processes that support engagement with industry, governments, other research institutions, and the general public.

MRL supports interdisciplinary materials research in a number of ways. Direct funding of interdepartmental research groups and seed grants for junior faculty are provided by the NSF MRSEC program as well as by other large programs such as the NSF Center for Quantum Materials. MRL also assists faculty in developing research programs supported through a range of sources that include most US federal funding agencies, domestic and international corporations, and state and international governments.

In the past year, there has been significant growth in support of multi-investigator programs centered in condensed matter physics. For example, QPress (Quantum Press for Next Generation Quantum Information Platforms), a new DOE-supported program led by Professor Pablo Jarillo-Herrero and Assistant Professor Joseph Checkelsky, began in FY2019. Another new DOE program, Creating and Probing Large Gap 2D Topological Insulators for Quantum Computing, will support the research of five faculty members starting in FY2020.

MRL also played a key role in the development of new pending proposals for large interdisciplinary research programs this year. One example is a proposal for a new NSF center, the Quantum Foundry for Layered Materials Exploration, that would provide support for 10 faculty members in the Department of Physics, EECS, and MechE as well as research instrumentation that would be located in both MIT.nano and MRL. In addition, MRL supported the formation of development teams that submitted a proposal for an NSF Materials Innovation Platform program for a laboratory/library focused on engineering and analytics of polymers. This proposed program, led by PI Katerina Ribbeck (BE) and co-PI Krystyn Van Vliet (DMSE), would support a team of 25 faculty from six departments and two schools and would create shared experimental facilities in MIT.nano and MRL. MRL's capacity to convene teams and build on best practices learned from other programs, particularly the NSF MRSEC program, is a critical component of MIT's ability to effectively compete for such programs. Although there is no guarantee that these proposals will be funded, the community building and interaction that occur during the development of the proposals will persist and support the collaborative pursuit of other funding opportunities.

Engagement with industry has been a special focus of MRL activity in the past year. A series of corporate innovation workshops were held to identify and implement new modes of collaboration between academia and industry, especially in the innovation process that leads from invention to technology. These workshops were held in collaboration with the National Academies of Sciences, Engineering, and Medicine and involved the MIT Innovation Initiative and representatives from over 20 corporations. As an outcome of the most recent meeting, working groups were created to focus on technology scouting, talent, and partnerships. These groups are now developing specific mechanisms for engagement in these areas. Although not the specific intent of these workshops, MRL has gained valuable insight from the events that has helped in the reinvention of its Industry Collegium through definitions of new value propositions for both industry partners and MIT faculty. One outcome of engagement with industry is support for research provided through grants from individual companies and consortia involving multiple companies, as well as through the four Manufacturing Innovation Institutes managed by MRL. Corporate support for MRL materials research has increased by 11% in the past year, and we anticipate continued growth in the coming years.

Major advances in instrumentation for materials research have been made in the last year. MIT.nano has become the home of two new cryo transmission electron microscopes for research on biomolecules and other soft materials, as well as an SEM/focused ion beam sample preparation system designed for use with these microscopes. MIT.nano has also developed new mechanisms and partnerships with instrument manufacturers that will provide other microscopy and materials characterization tools. These tools will complement existing facilities in MRL and will provide greatly needed extra capacity for materials characterization. The Department of Materials Science and Engineering has recruited two new faculty members with expertise in transmission electron microscopy, Professor James LeBeau (formerly of North Carolina State University) and Professor Frances Ross (formerly of IBM's T.J. Watson Research Laboratory). Professor LeBeau is arguably the leading innovator in methods for extreme-resolution scanning transmission electron microscopy, and Professor Ross has pioneered the development of new methods for in situ atomic-scale observations of dynamic materials processes including nanowire and quantum dot formation, electrodeposition, and corrosion. These new faculty members will allow MIT to establish a leadership role in setting the state of the art for instrumentation-enabled materials research. MIT.nano provides the only space on campus with the properties needed for operation of extreme-resolution tools, and a new scanning transmission electron microscope will be located there. MRL will be the home for new tools designed for atomic-scale in situ observations of dynamic materials processes.

MIT's NSF Materials Research Science and Engineering Center program will reach the end of its current six-year funding period in FY2020, and a proposal for funding of a new six-year program is under development. MIT was among the first set of recipients of these prestigious grants in the mid-1960s (then under a different name) and has received continuous support in the intervening years. Throughout this period, MRSEC has played a critical role in supporting interdisciplinary materials research at MIT and in creating and supporting shared experimental facilities for materials research. MRSEC support resulted in multi-investigator interdisciplinary research programs in areas in which MIT came to play a global leadership role, including quantum dots, integrated microphotonics, and Li-ion batteries. MRSEC has also nurtured research that led to many successful new enterprises. We look forward to a successful renewal of this important program in the coming year.

Non-MRSEC research volume as measured through expenditures increased by 14% in FY2019, to $19,487,368. Total research volume (including the MRSEC program) increased by 11.6%, to $21,852,530. The increase in non-MRSEC volume was associated largely with a new DOE Energy Efficiency and Renewable Energy program led by Professor Antoine Allanore and several new programs awarded from industry. As anticipated, several programs ended in FY2019, including the Lightweight Innovations for Tomorrow Manufacturing Innovation Institute and the Integrated Micro-Optical Concentrator program with ARPA-E.

MRL's total volume can be volatile, and it is difficult to reliably project future funding levels. The AIM Photonics program will wind down in FY2020 following its budget reduction in FY2019. Support of the educational and workforce development efforts associated with the AIM Photonics Academy, led by Professor Lionel Kimerling, will move from MRL to DMSE. Professor Kimerling is receiving encouragement from various DOD and state agencies with strong indications for new funding of this important activity. The Skoltech Center for Electrochemical Energy Storage will wind down in the first half of the upcoming fiscal year, while several new NSF-, DOE-, and industry-supported programs are likely to start in FY2020. We anticipate that total research expenditures will hold even or increase slightly in FY2020.

The formation of MRL less than two years ago created unprecedented opportunities to better serve the broad materials research community at MIT and to support engagement of that community with industry, governments, and other universities at both the national and global levels. In the past year, significant progress in capitalizing on these opportunities has been made. The leadership and staff look forward to further advances in all of these areas in the coming year.

Carl V. Thompson
Director
Stavros Salapatas Professor of Materials Science and Engineering