Research Laboratory of Electronics

The Research Laboratory of Electronics (RLE) at MIT is a vibrant intellectual community and was one of the Institute's earliest modern interdepartmental academic research centers. RLE research encompasses both basic and applied science and engineering in an extensive range of natural and man-made phenomena. Integral to RLE's efforts is the furthering of scientific understanding and leading innovation to provide great service to society. The lab's research spans the fundamentals of quantum physics and information theory to synthetic biology and power electronics and extends to novel engineering applications, including those that produce significant advances in communication systems or enable remote sensing from aircraft and spacecraft, and the development of new biomaterials and innovations in diagnostics and treatment of human diseases.

RLE was founded in 1946 following the ground-breaking research that led to the development of ultra-high-frequency radar, a technology that changed the course of World War II. It was home to some of the great discoveries made in the 20th century at MIT. Cognizant of its rich history and with a focus on maintaining its position as MIT's leading interdisciplinary research organization, RLE fosters a stimulating and supportive environment for innovative research and impact.

What distinguishes RLE today from all other entities at MIT is its breadth of intellectual pursuit and diversity of research themes. The lab serves its researchers by providing a wide array of services spanning financial, human resources (HR), information technology, and space renovations. It is fiscally independent and maintains a high level of loyalty from its principal investigators (PIs) and staff. With its diverse PI population, which is drawn from the Schools of Engineering and Science, RLE is in many ways the only lab that is "representative" of MIT as a whole, albeit on a much smaller scale. Every organization needs a testing ground for developing best practices and cultivating organizational learning and improvements. It is difficult and risky to experiment with an organization as large as MIT; a better approach would be to experiment on a much smaller scale with a highly aligned constituency that can provide rapid feedback and accelerate learning. RLE is ideally positioned to deliver on precisely that opportunity, that is, to become a test bed and development ground for organization initiatives and best practices at MIT. This role for the lab is being fulfilled on several important fronts. RLE has initiated a number of programs that address important lab objectives which, if successful, may be scaled to the Institute level. Examples include the Low Cost Renovation Study (LoCRS), which is designed to demonstrate a new, low-cost renovation model far below the Institute's average renovation cost, and the Translational Fellows Program (TFP), an initiative accelerating the rate of technology translation and creating jobs for postdocs.

With a research volume of $54.3 million in fiscal year 2016, the lab continued to be one of the Institute's leading research organizations. From 2015 to 2016, there was a 2.4% increase in research volume. RLE manages more than 225 active research projects and services for over 70 principal investigators. In fiscal year 2016, 319 graduate students and 109 undergraduates worked in various labs.

Since 2011, RLE has been endowed primarily by royalties from high-definition (HD) TV intellectual property developed by lab researchers. The proceeds of this endowment are the basis for RLE's discretionary activities and budget. Major research funding is provided by Department of Defense agencies, the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Department of Energy (DoE). Additional funding is provided by the government of Madrid, Deutsches Elektronen-Synchrotron, the Samsung Advanced Institute of Technology, and the National Aeronautics and Space Administration. Other projects are funded through industry and private foundations.

Mission: The Freedom to Focus on Transformative Research

The Research Laboratory of Electronics is committed to creating a stimulating and supportive environment for innovative research. As MIT's leading entrepreneurial, interdisciplinary research organization, it provides visionary leadership, vibrant intellectual communities, and superior administrative services. The lab strategically deploys resources to achieve excellence in research, education, and impact.

Our principles and values are centered around our mission of supporting the freedom to focus on transformative research. These values include transparency, having a productive and respectful atmosphere, full accountability and responsiveness, involved leadership and participatory management, and investing in the professional development of our employees. We are a learning organization with an emphasis on system building.

The lab is home to some of the Institute's most innovative research and strives to develop new administrative approaches and best practices. With nearly 700 researchers from 10 departments spread across the Schools of Science and Engineering, the lab is uniquely situated to embrace Institute-wide initiatives. To that end, RLE has created and continued a number of initiatives aimed at organizational improvement including the Low Cost Renovation Study, the Translational Fellows Program, the RLE Immersion initiative, and the Postdoc Leadership and Administration Network, as well as certification for RLE administrative assistants through the Leading Excellence in Administration Program.

Service Survey

To provide the highest level of service and look for new opportunities to help support our faculty, we assess our services every two years through a survey of RLE PIs. This survey measures levels of satisfaction, provides feedback on the quality and timeliness of our work, and offers the PIs a confidential forum for general commentary.

Research and Administrative Initiatives and Events

Intergroup Collaboration

Initiated in fall 2013, RLE Immersion was designed to bring RLE research groups together, to increase their exposure to one another, and to showcase research within RLE in a new and engaging way. This initiative increases intergroup collaboration and knowledge, strengthens the lab’s sense of community, and connects with RLE’s rich history and major achievements.

RLE is made up of diverse research labs that are grouped into seven major research themes. The themes range from bioengineering and biophysics to atomic physics and nanoscale materials, devices, and systems. Each theme is represented by a color that is incorporated in the marketing for all events, allowing for continuity and providing a framework for the community. The RLE community’s response to this initiative has been remarkable: member participation has exceeded expectations.

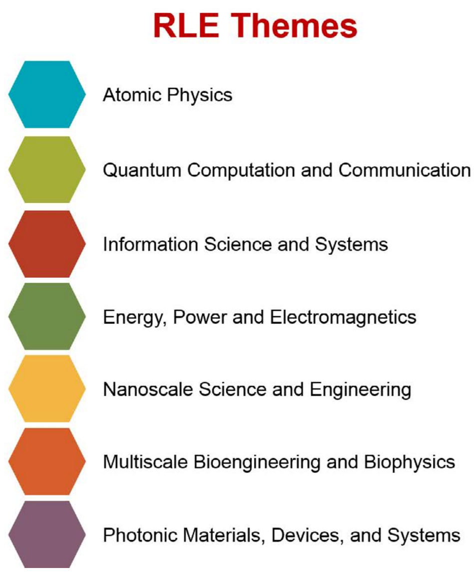

Figure 1. RLE’s seven major research themes.

Each theme is highlighted for a six-week period during the academic year with a series of events aimed at immersing the RLE community in the theme’s research area. The activities are orchestrated by the theme’s lead PI and a theme-wide student committee, with additional support from an RLE headquarters team. Each theme has a kick-off celebration, a full RLE social event with targeted research talks and posters highlighting the group’s research focus. One or more additional lab-wide activities take place during the theme’s spotlight period. RLE Immersion events provide structure, time, and a comfortable setting to allow for open conversation and engagement, potentially leading to new collaborations. The RLE Immersion initiative is designed to inspire and spark new ideas.

Translational Fellows Program

The Institute is committed to generating, disseminating, and preserving knowledge and to working with others to bring this knowledge to bear on the world’s great challenges. MIT is a center of innovation and technology with a distinguished legacy of important discoveries that have made a global difference. On an annual basis, approximately 20 start-ups based on research discoveries are created.

During 2015–2016, RLE followed up on the previous year's pilot of a postdoc-based program for the accelerated translation of research-derived technologies. The Translational Fellows Program has the dual goals of accelerating the transfer of these research-derived technologies into commercial products and creating professional development opportunities and jobs for postdocs. This competitive initiative provides funds for its fellows and a yearlong program tailored for value building and aimed at setting the stage for research translation and future venture success. Through this initiative, we work to bridge the gap in the chain of research-based innovation and accelerate the pace of technology translation, increasing the impact of MIT's research-derived innovations. Stakeholders from across the Institute benefit from this program:

- Postdocs have opportunities to acquire leadership skills, create job opportunities for themselves and others, differentiate themselves in the job market, expand their professional networks, and meet technology and industry experts. The program offers hands-on professional development, team-building activities, opportunities to develop new skills, engagement in the entrepreneurial MIT network, and the opportunity to create an exciting company in the process.
- Faculty are given an opportunity to have a technology developed in their lab commercialized, with the benefit of lower risk due to integrated conflict of interest management; 20% of postdocs' salary goes back into their research accounts.
- Departments are able to provide professional development opportunities for postdocs and lower risks associated with conflicts of interest.
- MIT benefits from the creation of job opportunities for postdocs and investments in their professional development, recognized as a key area for Institute improvement; from maximizing the impact of research-derived technologies; and from scaling the number of MIT start-ups benefiting the economy.
- Society benefits in terms of access to innovative products, job creation, and return on a significant investment in university research.

With the support of the MIT Innovation Initiative and engagement with departments and labs such as the Department of Biological Engineering, the Department of Electrical Engineering and Computer Science (EECS), the Department of Mechanical Engineering, the Microsystems Technology Laboratories (MTL), the Department of Materials Science and Engineering, and the Department of Physics, the program has expanded to include 16 postdocs. We also formed alliances with like-minded organizations and individuals across campus and beyond, involving the Martin Trust Center for MIT Entrepreneurship, the Industrial Liaison Program, and others. We extended and strengthened our collaboration with MIT's Venture Mentoring Service (VMS), facilitating the scale of mentorship—a key aspect of the program. All fellows were matched with teams of three to five VMS mentors and had frequent interactions via either team mentoring sessions or one-on-one consultations.

The current year is critical in refining the scalability of TFP, with the number of accepted postdocs expanded to 50. A modular approach has been designed allowing us to support this target in two cohorts of 25 postdocs each. It is anticipated that this approach will enable us to continue to scale and grow the program in subsequent years by adding further cohorts to reach 100, 200, and as many as 300 fellows supported annually while employing various processes to ensure continuous learning and improvement. Naturally, expansion is contingent on favorable outcomes.

Lincoln Laboratory Collaboration

To promote collaborations and seek funding for joint research proposals, we are matching RLE PIs with key Lincoln Laboratory personnel. In continuing the development phase this year, we established the framework and worked closely with Dr. Bernadette Johnson, Lincoln Laboratory's chief technology officer, to determine preliminary matches.

Low Cost Renovation Study

RLE has continued investigating the cost drivers behind on-campus renovations. In cooperation with the MIT Department of Facilities, the Low Cost Renovation Study is based on a collaborative approach to gathering data and jointly assessing the renovation process. One of the study's objectives is the creation of a tightly integrated model for renovations that are cost effective and high quality, compliant with safety codes, and have the ability to scale. With more than 100,000 square feet under management, the lab is a prime candidate for such an examination. RLE is home to diverse research areas and is large enough to be significant, yet small enough to execute projects quickly and with expertise. The Department of Facilities has commissioned RLE to expand the study to include two more external projects: the renovation of the Kavli Institute for Astrophysics and Space Research and a lab renovation for RLE PI Terry Orlando in Building 13.

The initial LoCRS renovation project, begun in early 2013, involved a remodel of RLE PI Dirk Englund's lab, a 1,460-square-foot space in Building 36. At the time, average MIT lab renovation costs were hovering around $1,000 per square foot. The final cost of the RLE-managed Englund renovation was $310 per square foot.

Our findings to date support the hypothesis that a renovation process managed by a department, lab, or center (DLC), with an MIT Facilities liaison, can produce a cost-effective, high-quality result.

As part of the LoCRS process, RLE developed a guide for DLCs on self-managing small-scale renovations. The guide covers the full scope of the renovation process, including pre-construction, construction, and final inspection phases. LoCRS also takes into account the scale of the project and use of space.

Postdoc Leadership and Administration Network

RLE has continued to provide workshops to develop the leadership skills of our postdoc community through the Postdoc Leadership and Administration Network (PLAN). PLAN allows postdocs to learn, converse, and integrate leadership and administrative skills to help prepare them for becoming faculty or industry leaders. All PLAN workshops are designed to provide practical advice as well as tools and techniques for applying best practices in leadership and management.

Current and Pending Report Generator Tool

RLE senior financial assistant Stephanie Muto developed a current and pending (C&P) report generator tool that helps reduce the amount of time and effort involved in creating C&P reports for proposals or annual progress reports. Stephanie has shared the C&P generator with several departments and is advising the Kuali Coeus team in the Office of Sponsored Programs on an adaptation that could be made available to all of MIT.

Leading Excellence in Administration Program

RLE continued the Leading Excellence in Administration Program (LEAP) for RLE administrative assistants. This monthly training program was created to support and enhance the assistants' administrative, human resources, fiscal, and computer skills. Program content was designed to keep assistants abreast of current best practices, inform them of the latest updates to MIT processes, and educate them about ongoing administrative initiatives within RLE. Some of the topics covered were HR management, research account management, stress management, conflict resolution, new procurement procedures, and MIT's off-campus housing options. This year, we introduced a brown bag series that supplemented the monthly training sessions with soft skill workshops on tools such as Duo, Dropbox, calendar management and WebEx. Many of these sessions were taught by RLE assistants and provided professional development opportunities. This year's PI survey confirmed that LEAP is one of RLE's most successful initiatives and is making a positive difference in value added to the PIs, as well as easing the burden on headquarters. Sixteen assistants received a certificate of completion: Teresa Avila, Janice Balzer, Fionnuala Coary, Chadwick Collins, Susan Davco, Shirley Eintzminger, Shayne Fernandes, Dorothy Fleischer, Cindy LeBlanc, Josephina Lee, Michael Lewy, Hien Nguyen, Tricia O'Donnell, Read Schusky, Laura von Bosau, and Arlene Wint.

Laboratories and Research Highlights

The 2015–2016 academic year saw many awards, recognitions, and milestones for RLE investigators. The following is a summary of RLE research highlights from the past year.

Atomic Physics

Research in atomic physics at RLE encompasses investigations in ultra-cold atoms, quantum condensed gases, and atom optics. New methods are being developed for manipulating and probing Bose-Einstein condensed atomic gases and exploring ultra-cold interactions and collision dynamics in bosons and fermions. Additional work focuses on atom lasers, atom interferometry, atom waveguides, surface physics, quantum reflection, many-body physics in lower dimensions, plasmas, and electromagnetics.

Professor Wolfgang Ketterle's research focuses on the properties of bosonic and fermionic quantum gases. He and his group use ultra-cold atoms to realize new forms of matter with strong interactions and strong correlations. In this way, they perform quantum simulations of simple Hamiltonians. Quantum degenerate gases are novel systems to study many-body physics such as phase transitions, superfluidity, and vortices. The current focus of their program is quantum magnetism, that is, the ordering of spins. In addition, the group studies ultra-cold molecules and their reactions.

The possible applications of their work, including coherent atom sources based on Bose-Einstein condensation, may replace conventional atomic beams in demanding applications such as atom interferometry, precision measurements, future atomic clocks (which provide the time and frequency standard), matter wave microscopy, and the creation of microscopic structures by direct-write lithography. In addition, ultra-cold gases of bosonic and fermionic atoms are quantum fluids, which have properties different from the quantum liquids helium-3 and helium-4. Therefore, it is now possible to study macroscopic quantum phenomena in a new regime.

The Ketterle group recently observed, for the first time, Bose-Einstein condensation in high synthetic magnetic fields. Over the last few years, the Ketterle team and other groups have developed techniques to make neutral atoms behave like charged particles in magnetic fields. Using laser forces, the neutral atoms are exposed to the same Lorentz force that deflects electrons in magnetic fields. The Ketterle group has now reached Bose-Einstein condensation in such a system, which is the starting point for obtaining new insights into phenomena at high magnetic fields.

The research of Professor Vladan Vuletic focuses on how large quantum mechanical systems can be used to improve atomic sensors and atomic clocks. This year, Professor Vuletic's group reported the non-destructive detection of a single photon. In all standard photodetectors, light is detected by destroying it, converting it into heat or an electrical signal. In the new detector, the photon is detected without destroying it; detection occurs while the photon is traveling through a special optical medium where it is reversibly converted into an atomic excitation that can be optically measured and then converted back into a photon upon exiting the medium. This detector may have applications for secure long-distance quantum communication.

Professor Vuletic and his group also continued their studies of the fundamentals of friction. After showing so-called superlubricity in an atomic simulator—the strong reduction of friction by a slight rearrangement of the sliding surfaces so that they are made incommensurate—they showed that superlubricity is closely related to the famous Aubry transition that governs the fractal arrangement of a chain of atoms in an incommensurate periodic potential. This possibility of reducing or tuning friction may be important for nano-machines that, due to their much larger surface-to-volume ratio, suffer much more severely from frictional dissipation than macroscopic objects.

Professor Martin Zwierlein's group in experimental atomic physics uses atomic and molecular gases at ultra-low temperatures to realize novel states of matter and to perform experimental tests of quantum theories from condensed matter and nuclear physics. The interactions between the particles in these gases can be made as strong as quantum mechanics allows. The group is running three experiments, all focusing on the study of fermions, particles with half-integer spin such as electrons. Fermions have to obey the Pauli principle, the constraint that no two fermions can occupy one and the same quantum state. This principle underlies the periodic system of elements and explains the stability of neutron stars against gravitational collapse; however, when fermions strongly interact, such as the electrons in high-temperature superconductors, theoretical predictions become extremely difficult. This is the perfect place to look for novel states of matter and to uncover how nature deals with strongly interacting fermions.

This year saw two major breakthroughs in the Zwierlein group's research: the creation of Mott insulators under the group's Fermi gas microscope and the observation of second-scale coherence times in a Fermi gas of ultra-cold molecules.

The Fermi gas microscope allows imaging on the order of 1,000 individual fermionic atoms stored in an artificial crystal of light. Such light crystals or optical lattices are ideal platforms to simulate solid state systems with atoms rather than electrons. One of the most important open questions in condensed matter is the physics of high-temperature superconductors. The Fermi-Hubbard model of fermions hopping and interacting on a lattice is believed to capture the essence of this physics. However, this model cannot be solved on today's computers at low temperatures due to the intricate interplay of the Pauli principle and strong interactions.

Zwierlein and his group realized low-temperature phases of the Fermi-Hubbard model under the microscope, where they were able to resolve every atom involved, and observed metallic band insulating and Mott insulating states. A Mott insulator does not conduct particles, not because all available states are occupied but because transport is inhibited by interactions. Seeing this physics atom by atom represents a breakthrough in our ability to understand the Fermi-Hubbard model. If temperatures can be lowered by another factor of about five, physics that cannot be simulated on classical computers can be explored.

The second breakthrough was achieved in the group's experiment on ultra-cold fermionic molecules. Molecules have long been proposed as a resource for quantum information and computation. Their rich degrees of freedom—electronic, vibration, rotation, and nuclear spin—seem ideal for storing quantum information and implementing quantum gates. Last year the group produced the first chemically stable Fermi gas of ultra-cold molecules and soon gained control over their rotational and nuclear spin degrees of freedom via microwave drives; they were then able to produce quantum superpositions of nuclear spin states. They observed a record second-scale coherence time for this superposition in their gas, which contained several thousand molecules. This represents a thousand-fold improvement in the coherence time of ultra-cold molecules and makes these molecules extremely interesting for quantum information applications. The long coherence times stem from several factors, including the absence of electron spin in the electronic ground state of these molecules and the fact that the molecules are fermions and therefore do not collide head-on. Zwierlein and his group believe that the combination of long storage times in nuclear spin states and strong interactions between molecules induced by rotational transitions could make molecules a promising platform for quantum information processing.

The two highlights just described nicely represent the two major directions in the field of ultra-cold atoms: the use of these gases as quantum simulators of other systems in nature (high-temperature superconductors, neutron stars, etc.) and the motivation to discover novel states of matter at ultra-low temperatures that do not exist naturally. It would be ideal to combine the two experiments (which took place in two different laboratories, with different groups of students) and realize a quantum gas microscope for molecules. This setup might be the best way to realize a quantum computer based on molecules, something that was proposed over a decade ago. The Zwierlein group is now uniquely positioned to mount a serious effort in this direction.

Energy, Power, and Electromagnetics

This theme comprises work in excitonics, studies in the absorption and emission of light, solar cells, disordered and low-dimensional materials, complex nanostructures, organic light-emitting diodes (LEDs), nanowires, hybrid organic-inorganic materials, organic structures and devices, power electronics, signal-level control circuits and electronics, system identification and control, continuum electromechanics, and high voltage and insulation research.

Professor James Kirtley of the Laboratory for Electromagnetic and Electronic Systems (LEES) is a specialist in electrical machinery and electric power systems. Over the past year, his group has made progress in a number of different areas. For example, the group's small-scale micro-grid analog emulator has been used to investigate, along with simulation, the stability of small-scale micro-grids with induction motor loads. An energy-based direct method for assessing critical clearing time in these small micro-grids has been developed, and a method for enhancing transient stability has been developed and demonstrated. In addition, the capacity of the system has been enhanced with a second engine-generator emulator so that inter-area swings between multiple micro-grids can be investigated. The development of this analog micro-grid emulator is motivated, in part, by a collaboration between Kirtley's team and members of the Electric Power Systems group at the Masdar Institute in the United Arab Emirates (UAE). Dr. Mohamed Al Hosani, an assistant professor at Masdar, spent several months in residence with Kirtley's group. Now back in the UAE, Dr. Al Hosani is starting a collaborative research project on the stability and dynamics of micro-grids with Kirtley and Professor Konstantin Turitsyn of the Department of Mechanical Engineering. In a related project, members of Kirtley's group have delivered to a sponsor a package of software modules for simulating components of micro-grids. Some of those modules were used in the study of induction motor transient stability.

During the year, a PhD student working with Kirtley and Professor Leslie Norford of the Department of Architecture finished a project in which he demonstrated the ability to provide ancillary services to utilities, including both voltage and load/frequency support, by modulating air-conditioning motors with variable-speed compressors.

Working with MIT professor Steven Leeb, Dr. Kirtley and a PhD student concluded an investigation of large motor drives for ship propulsion. Their doubly fed induction motor drive was demonstrated to run as predicted. It has the ability to achieve a bumpless transition between low-speed stealth and high-speed doubly fed machine modes of operation. The project will continue with another PhD student demonstrating a doubly fed generator to allow for a complete ship propulsion and power system.

The team's work on compact permanent magnet motors for mobile robots, in association with Professor Jeffrey Lang and a PhD student, has concluded. An experimental motor has been designed, built, and tested. That work has been extended to other mobile applications such as bicycle wheels. An investigation into switched flux motors for motorcycle application has shown that this motor morphology is probably not the correct one for compact wheel motors and that surface mount permanent magnet motors are likely a better solution.

Under the sponsorship of the Tata Center for Technology and Design, part of the MIT Energy Initiative (MITEI), Dr. Kirtley is embarking on an effort to build better appliance motors. After an information-gathering visit to India, the objective has shifted to providing increased efficiency, that is, more impact per unit of energy input. The effort will likely include more fans, pumps, and home appliances, in addition to more efficient motors with better power factors.

Professor Jeffrey Lang's research generally focuses on the analysis, design, and control of electromechanical energy-conversion and motion-control systems. Its applications typically involve high-performance electrical machine systems, micro-scale and nanoscale electromechanical actuators and sensors, and distributed electromechanical structures.

A team of graduate students and postdocs under the supervision of Professor Lang and Professors Vladimir Bulović and Timothy Swager have demonstrated a nanoelectromechanical (NEMS) relay that operates with an organic molecular monolayer between its contacts. The relay is closed via electrostatic actuation, typically below 1 V. When closed, the relay conducts via tunneling through the molecular monolayer; when open, its conduction reduces by a factor of approximately 10^6. The importance of the molecular monolayer is that it prevents contact stiction, thereby eliminating a major impediment to using NEMS relays for low-voltage digital logic and radio frequency switching. Analog extensions of the relay include high-gain low-voltage valves and electrically tunable nanoscale gaps for plasmonic applications. Current work focuses on reducing actuation voltage and energy, improving fabrication yield, and simultaneously increasing the ratio of on-state to off-state conduction. Over the past year, the group has have developed a process enabling fabrication of electrically adjustable nanometer-scale gaps that are foundational to the aforementioned devices. The process, which involves chemical syntheses, self-assembly, continuum electromechanics, and molecular engineering, appears to be scalable to circuit-level complexity with device interconnects.

Professor Lang, graduate student Matthew D'Asaro, and undergraduate student Daniel Sheen have developed a low-cost rugged sensory skin that can differentiate between pressure and shear. Applications range from providing a sense of touch to robot hands to the reanimation of touch in human limbs that have suffered injury. Recent work has improved the selectivity and sensitivity of the skin to pressure and shear, as well as its immunity to external disturbances, and has enabled its fabrication over wide areas.

Professor Steven Leeb is also part of LEES. Professor Leeb's group has had an extraordinary year developing systems for controlling and generating energy. Specifically, Professor Leeb and his team have:

- Obtained a US patent for a new circuit topology that minimizes the need for capacitive energy storage in grid-interface power converters. This work was conducted in collaboration with Professor David Perreault's group. The patent has been licensed through MIT's Technology Licensing Office.
- Developed the "Electronic Stethoscope," a new sensor that decodes the voltages and currents in a wire bundle or other conductor array from "non-contact" measurements of electric and magnetic fields around the wire. New signal processing algorithms have been developed that solve the "inverse problem" of reconstructing internal voltages and current levels from "free air" measurements with high specificity. Four of the systems were installed this year on the US Coast Guard cutter Spencer stationed in Boston's North End, and they are being used for on-board energy scorekeeping and diagnostic monitoring. Results from this work will lead to larger field studies in the near future.
- Developed a new power electronic technique for spread-spectrum wireless energy transmission and inductive charging for medical and other applications. This work was conducted with Professor Al Avestruz, an MIT PhD who completed his work in Professor Leeb's group this year and is now on the faculty at the University of Michigan in Ann Arbor.
- Created a use for their doubly fed induction machine, as a doubly fed induction generator in microgrid arrays. The group is currently exploring this new approach, which minimizes power electronic ratings and affords unique levels of control, for shipboard power applications.

Professor David Perreault's research focuses on advancing power electronics technology and the use of power electronics to benefit key applications. Major research thrusts include the development of extreme high-frequency power conversion to attain miniaturization and integration, the development of power converters with greatly improved efficiency, and the use of power electronics for applications such as solar photovoltaics and grid-interface power supplies. One valuable area of research this year has been the investigation and characterization of power magnetic materials for use at high frequencies (3–30 MHz). This work, which has led to a conference paper and a journal paper, is valuable for designing power electronic converters operating in the high-frequency regime; Perreault and his group are using the results of this effort to develop universal-input power supplies for grid interfaces operating at high frequencies. They have also been exploring reconfigurable power circuit architectures that can provide high efficiency over wide operating ranges. One aspect of this investigation has led to a new topology for high-efficiency large-step-down DC-DC conversion that preserves high efficiency over a wide power range. The group's prototype design for 380 V to 12 V conversion at 300 W yields a full-load efficiency of 96%, a peak efficiency of 97%, an efficiency of 93% at a load of 10%, and an efficiency of 80% at a load of 3.3%.

The research of Professor David Trumper, a member of LEES, is focused on precision mechatronics applied to a wide range of problems from health care to precision manufacturing. Over the past year, Professor Trumper and his group have worked on seven major projects:

- The group has been studying the design of high-force linear motors for rapid and precise positioning in applications such as semiconductor manufacturing.
- In a collaboration with Professor Linda Griffith, the group has been designing mechatronic solutions for novel multi-organ human tissue bioreactors. This research is leading to the creation of new microphysiological systems for in vitro studies of human organ tissues such as lung, gut, endometrium, and liver cells.
- In another collaboration, with Professor Griffith and Professor Rebecca Carrier of Northeastern University, the group is designing mechatronic solutions for microphysiological systems that will allow studies of human gut behavior in the presence of gut bacteria as well as gut-liver interactions.
- In work with Professors Jeff Lang and Markus Zahn, Professor Trumper is investigating an electromagnetic nano-imager that uses electric and magnetic fields to image surfaces with nanometer-scale resolution.
- Professor Trumper is working with an industrial partner to design new types of magnetically levitated impellers for blood oxygenation pumping.
- In a collaboration with the Masdar Institute of Science and Technology, the group is designing new approaches for solar energy collection and storage in a molten salt system.
- In a new collaboration with Lincoln Laboratory, the group is designing a new type of momentum wheel for microsatellite attitude control.

Information Science and Systems

Research in this area spans a complete range of activities covering all aspects of electronics, including structures, devices, and circuits; analog and digital systems; microelectromechanical systems (MEMs) and bioMEMs; nanotechnologies; numerical and computational simulation and prototyping; biologically inspired systems; digital signal processing; advanced telecommunications; medical imaging; and the exploration of fundamental issues in wireless networking and devices.

Research in Professor Vincent Chan's group focuses on ultra-high-speed and high-quality-service heterogeneous networks and their particular relevance to defense network and cyber security. Their work includes applications over satellite, wireless and optical communication, and heterogeneous data networks. The objective is to develop the scientific base needed to design data communication networks that are efficient, robust, and architecturally clean, as well as study application scenarios and their modeling to enable research and development of the "right" network architecture. Their work in the past three years on heterogeneous networks has stimulated worldwide research in the area; notably, Singapore's government initiated a heterogeneous network project that involves industry, academia, and government research labs. Professor Chan's group is acting as an adviser for the project.

In the group's optical network "Large Internet Collaborative" program funded by the National Science Foundation, MIT serves as the chief architecture source for future optical networks, with Stanford University, the University of Texas, and Bell Laboratories as partners. Through collaborative efforts with Bell Laboratories and the University of Texas at Dallas, the MIT team invented a new algorithm to dynamically turn on and off wavelength channels in fiber networks. A worldwide patent has been filed that will see usage in the new paradigm of agile large-bandwidth transports for data center and bid data applications.

On the optical security front, a study of new attack mechanisms on optical networks was performed. Mitigation techniques were proposed, and in the next few years these techniques will be further developed into usable architecture constructs. To protect the data integrity of existing high-speed optical networks, a new cryptographical system for optical networks based on readily implementable classical techniques was invented and a patent filed.

In terms of reliable network delivery of critical messages, a new routing and transport algorithm was created to ensure timely delivery of messages such as disaster warnings.

The Energy-Efficient Circuits and Systems Group, led by Professor Anantha Chandrakasan, investigates new circuit-level and architectural techniques to enable improvements in energy efficiency for a wide range of integrated electronic systems. Example application domains include the Internet of Things, biological sensors, multimedia processing, and energy conversion. One highlight from the group this year is its demonstration of a low-power wireless readout system for whole-cell biosensors.

Whole-cell biosensors are living cells that are genetically engineered to sense specific targets. A key advantage of using cells as sensors is the ability to sense molecules in environments that would otherwise be challenging for immunoassay-based tests. Example applications include monitoring water quality by sensing toxins and contaminants and monitoring someone's health by sensing biochemicals inside the body itself. To enable widespread use of whole-cell biosensors, low-power readout mechanisms are required. Bioluminescence readouts are generally performed with large laboratory-based equipment that consumes watts of power.

In collaboration with Professor Timothy Lu's Synthetic Biology Team, the group has been investigating circuit techniques for even lower power readouts from whole-cell biosensors at the nanowatt level. At this power level, readouts can be performed using energy scavenged from the environment or supplied by a millimeter-scale thin-film source, enabling applications such as ingestible sensors.

The group has developed a system that performs bioluminescence readouts from cells while consuming as low as 5 nW of average power (10-minute sampling interval), in part by leveraging the slow time constants of the biology. To perform the signal conversion, a phototransistor detects the low-intensity luminescence and a time-based threshold-crossing scheme is used to quantify it. Toward an ingestible sensor for blood in the gastrointestinal (GI) tract and in collaboration with Professor Lu's team, the group demonstrated this design for in vitro sensing of blood using luminescing whole-cell sensors. They are currently working on optimizing the wireless link and miniaturizing the device to demonstrate fully wireless in vivo sensing.

With the continued expansion of the Internet of Things, this research can further enhance the capabilities of low-cost microelectronics in the area of environmental and physiological sensing. The ability to sense small molecules using a synthetic biology foundation can enable new types of low-cost sensors for environmental or connected health monitoring.

Professor Luca Daniel leads the Computational Prototyping Group with Professor Jacob White. The group uses several engineering design applications to drive research in simulation and optimization algorithms and software, with efforts focusing on the fundamentals of model-order reduction, matrix-implicit methods, fast techniques for solving integral equations, and uncertainty quantification.

Brain-inspired arrays of parallel processing oscillators are an intriguing alternative to traditional computational methods for data analysis and recognition. This alternative is now becoming more concrete thanks to the advent of emerging oscillator fabrication technologies, such as those being developed by the group of MIT professor Dana Weinstein, which can provide high-density packaging and low power consumption. Challenging issues related to oscillator arrays include the large number of system parameters and the lack of efficient computational techniques for array simulation and performance verification. To address some of these issues, Professor Daniel and his group have developed a methodological approach to the analysis and design of arrays of resonant oscillators for associative memory applications. They have further developed a realistic phase-domain model of the oscillator array that can incorporate the relevant non-idealities of practical implementations. Relevant non-idealities are the nonlinear nature of coupling, the limited achievable coupling strength, and the variability of oscillating frequency and phase noise. Simulations have revealed that for very small frequency variability, the correct associative memory behavior holds for a wide range of coupling strength. By contrast, for relatively large frequency variability, associative memory performance is strongly affected by the coupling strength. In this case, the proposed phase-domain macro-model provides an invaluable aid to the array design and to the definition of proper recognition timing.

In addition, Professor Daniel's group used tensors (namely, a higher order generalization of matrices) to develop a new nonlinear model order reduction algorithm for the efficient simulation of nonlinear circuits and systems. The use of tensors allowed the group to capture efficiently high-order nonlinearities with just a few vectors obtained from a canonical tensor decomposition. Standard projection-based model order reduction can then be employed with those vectors to generate compact reduced-order models. The key feature of this approach is that it exposes and exploits the inherent sparsity of many high-dimensional circuits and systems, thereby reducing memory requirements and speeding up computation. The approach has been tested on a variety of nonlinear circuits and systems via both transient and periodic steady-state analyses. In all cases the approach demonstrated superior accuracy and efficiency, particularly in highly nonlinear scenarios.

Over the past year, the work of Professor White's group focused on low-cost hardware-centric courses in edX and internationally (in Nigeria and at the Skolkovo Institute of Science and Technology), scalable optimization approaches for large-scale power system stability certification, spectroscopic inspection, simulation of integrated ED (electrodialysis) and ICP (ion concentration polarization) desalination, volume integral equation methods for fast extraction from process emulations in integrated terahertz circuit and nanophotonic designs, electromagnetic field analysis in magnetic resonance imaging (MRI), and low-cost open-source shim-coil drivers for magnetic resonance imagers. Below are brief descriptions of two of the group's projects.

The rate of electric-field-driven transport across ion-selective membranes can exceed the limit predicted by Nernst (the limiting current), and encouraging this "overlimiting" phenomenon can improve efficiency in many electrochemical systems. Overlimiting behavior is the result of electroconvectively induced vortex formation near-membrane surfaces, a conclusion supported by two-dimensional (2D) theory, numerical simulation, and experiments. Professor White's group showed that the three-dimensional (3D) situation is quite different; specifically, the vortex pattern in shear flow through wider channels is helical rather than planar, a surprising result first observed in 3D simulations and then verified experimentally. The group also showed that, similar to overlimiting current and overlimiting conductance, the number of parallel helical vortices is a jump-discontinuous function of width. In addition, the group found that overlimiting occurs at lower fields in wider channels, because the associated helical vortices are more readily triggered than the planar vortices associated with narrow channels (effective 2D systems). These unexpected width dependencies arise in realistic electrochemical desalination systems and have important ramifications for design optimization.

In January 2016, a "beta" edX course was offered as an experiment in using physical hardware to teach introductory control theory. The course was unique in that it was based on commodity hardware purchased and assembled by students and on public-domain and custom open-source software. In addition, the course was carefully designed around the inexpensive, and therefore imprecise, student-developed hardware. Students who learned the technically deep concepts could use those concepts to improve the performance of controllers they designed for their own hardware. Developed in under six months, the course has already involved thousands of students worldwide. They are building the hardware, designing and testing controllers, and even posting YouTube videos to demonstrate their results.

In their work, Mildred Dresselhaus and her group focused on using science to have an impact on society. Professor Dresselhaus received the IEEE (Institute of Electrical and Electronics Engineers) Medal of Honor last year—the first woman to receive the award in the its 100-year history—for her ideas on using nanoscience, new materials, and new approaches to stimulate exploration.

New results of special interest were obtained in research involving low-dimensional materials, with measurements made on the vibrations of a single linear chain of carbon atoms inside the hollow of a double-wall nanotube used to house the carbon chain, enabled by the unusually high frequency measured on the chain of carbon atoms. These findings were particularly interesting because progress with this idea had been made in recent years by a team of long-time MIT group members and collaborators. Professor Morinobu Endo of Shinshu University in Japan and former MIT PhD student Antonio Souza Filho from Fortaleza, Brazil, were the key people leading this experimental study.

During the past year, the Dresselhaus group published a number of invited review articles on various topics including double- and triple-wall carbon nanotubes and two-dimensional transition metal dichalcogenide clusters, ribbons, and sheets. Collaborations with EECS/RLE professor Jing Kong were essential for the preparation of interesting new materials, and Professor Tomás Palacios was key in helping the group members find applications for their work, for example the publication with Professor Bunshi Fugestsu from the University of Tokyo of efforts to mitigate the effect of radiation release from the Fukushima nuclear energy production plant caused by the tsunami in 2011.

Professor Jeffrey Grossman and his team focused on the computational and experimental design of novel materials for applications in water, energy conversion, and energy storage. Significant results from this year include the development of centimeter-scale graphene oxide membranes that reject particles down to 1.4 nm in size and show resilience to harsh chemical environments and high temperatures. These membranes have applications in a wide range of separation processes in which they can provide increased efficiency and lower energy consumption over a longer lifetime. Another recent highlight is the development of a new technique for large-area conformal coating of solar thermal fuels using electrophoretic deposition, allowing heat to be captured, stored, and released on demand in any form factor, including fibers.

Professor Jae Lim's group is involved in the development of image and video processing methods. One of the group's accomplishments over the past year was the development of new transforms that adapt to different parts of images and videos. This work has the potential to be useful for the development of more efficient image and video compression systems. Another accomplishment was the application of a color image model to reducing noise in color images. This work has the potential to enhance the quality of color images.

Professor Muriel Médard leads the Network Coding and Reliable Communications Group, a highly cooperative research group with collaborations that include the Computer Science and Artificial Intelligence Laboratory, the Microsystems Technology Laboratories, Draper Laboratory, and the Laboratory for Information and Decision Systems, as well as Aalborg University, Alcatel-Lucent, Australian National University, Ben Gurion University, Boston University, the Budapest University of Technology and Economics, the California Institute of Technology, the Chinese University of Hong Kong, CodeOn, Duke University, École polytechnique fédérale de Lausanne, Fraunhofer Institute, Heibei University of Engineering, KTH Royal Institute of Technology, Maynooth University, Northeastern University, New York Univeristy, Pennsylvania State University, Rutgers University, Schlumberger, Steinwurf, TU Braunschweig TU Dresden, the University of Connecticut, the University of Pennsylvania, Technicolor, Technion, Texas A&M, Trinity College Dublin, the University of Auckland, the University of Porto, and the University of Vigo. The group's central theme is networking, with a special emphasis on new practical and theoretical developments in the area of network coding. Achievements during the past year include both theoretical and practical work in developing information theoretic approaches to password protection, new algorithms for storage and distribution in volatile networks, applications of network coding in network reliability, and new information theoretic results that illuminate the limits of multiple-input/multiple-output antennas. Professor Médard received a James Evans Avant Garde Award from the IEEE Vehicular Technology Society recognizing the group's work.

Professor Vivienne Sze and the Energy-Efficient Multimedia Systems Group focused their research on development and implementation of energy-efficient and high-performance systems for various multimedia applications such as computer vision, machine learning, and video compression. Their work traverses various levels of abstraction from energy-aware algorithm development for signal processing to efficient architecture design and low-power very-large-scale-integration circuit implementation. The group's work this year has concentrated on two areas: energy-efficient hardware acceleration for the processing of deep convolutional neural networks (DCNNs), which provide state-of-the-art accuracy in a wide range of machine learning tasks (e.g., object classification, speech recognition), and joint architectures and algorithm designs for energy-efficient real-time object detection in embedded sensing applications (e.g., security, smartphones). Their work on an energy-efficient reconfigurable DCNN accelerator (named Eyeriss) provides 10-fold higher energy efficiency than mobile graphics processing units. Also, the object detection accelerator consumes less than 1 nJ per pixel for high-definition 1920 × 1080 video in real time, enabling object detection to be as energy efficient as video compression at less than 1 nJ per pixel. This is an important step toward achieving continuous mobile vision, which will benefit applications such as wearable vision devices for the blind.

Professor Gregory Wornell's research has focused on new technologies and algorithms for advanced sensing and imaging, new architectures for resource-efficient computing and storage, and embedded learning systems and techniques. In the area of advanced sensing and imaging, the Wornell group has made progress in two efforts. In one effort they have developed new techniques for optimizing antenna array design and sensor placement based on submodular function theory, and in the other they have developed new methods for using active imaging techniques to "see around corners" (i.e., to reconstruct objects that are viewed only indirectly via light bouncing off walls and other diffuse reflecting surfaces). Their computational imaging methodology is based on joint use of time-of-flight and signal-strength information.

The group also obtained key results in the area of new architectures for resource-efficient computing and storage. First, they determined how to best use redundant computation in cloud computing to make efficient tradeoffs between latency and machine time in cloud computing infrastructure. Interestingly, their results showed that the level of redundancy that should be used depends critically on an easily measured parameter of the response characteristics of the servers in the system. Second, they developed a design methodology for reconfigurable digital hardware based on the use of aggressively scaled (and ultimately unreliable) devices with appropriate levels of redundancy.

Finally, in the area of embedded learning systems and techniques, the group developed two new low-power information-conversion architectures. First, they developed a new automatic speech recognition (ASR) architecture for mobile device applications that consumes much less power than conventional ASR systems. Their approach uses analog dimensionality reduction techniques to reduce the downstream data conversion, digital processing, and deep learning engine requirements. Second, they developed a new analog-to-digital converter architecture that dramatically reduces the number of bits (and thus power) required to achieve a given level of data conversion quality. Their approach is based on novel analog-domain modulo preprocessing, which can be efficiently implemented in the phase domain.

Professor Lizhong Zheng and his team have been working on applying information theory to high-dimensional multimodal data processing. Based on a newly developed geometric structure, Professor Zheng's group has solved one of the central problems of data processing, the problem of feature extraction without the prior knowledge of a statistical model. Formulating this as a universal inference problem, they showed that optimizing certain information theoretic metrics indeed provides the optimal inference performance. This result gives new operational meaning to information metrics, which have mainly been used in the context of coded digital communications. The result also laid the theoretical foundation for how to process, exchange, and evaluate partial information in general data processing, which is a significant conceptual step toward generic and flexible data processing.

The Zheng group is currently applying this algorithm to a wide range of practical problems in areas such as personalization/recommendation systems, community detection in social networks, identification based on audio signals and images, financial systems, and cyber security systems. Zheng believes that his group's approach will have an impact in defining a new architecture in the data processing industry in the future.

Biomedical Science and Engineering

This theme encompasses thrusts in bio-inspired electronics and neural prostheses for hearing and sight, nano- and micro-technologies for understanding and manipulating biological processes at the cellular and molecular levels, imaging and computational modeling of disease and neuro-anatomical processes, and communication biophysics for language, speech, hearing, and haptics, including speech synthesis and recognition, sensory communication in all modalities, and the physiology of auditory perception and speech production.

Professor Elfar Adalsteinsson and the Magnetic Resonance Imaging Group focused on medical imaging via MRI, with ongoing developments in estimation of brain oxygenation parameters, parallel transmission technology, image reconstruction methods for accelerated acquisitions through undersampling, and imaging of the unborn child and placenta. New NIH funding was awarded for a four-way collaboration among Professor Adalsteinsson, Professor Polina Golland at MIT, Professor Ellen Grant of Boston Children's Hospital, and Larry Wald of Massachusetts General Hospital that will expand ongoing work in the relatively underserved space of fetal imaging to the study of the placenta via MRI.

The final contractual date for the Madrid-MIT M+Visión Consortium was June 30, 2016. Along with Professor Martha Gray, Professor Adalsteinsson served as associate director of the consortium, which recruited 34 fellows, engaged a cohort of over 100 collaborators on both sides of the Atlantic, and filed 25 intellectual property disclosures.

The work in the Bioelectronics Group, led by Professor Polina Anikeeva, revolves around developing minimally invasive approaches for interrogating and monitoring neural activity. Over the past year, the group has developed a wireless approach to local delivery of neuromodulatory compounds to specific neurons. This approach relies on the synthesis of highly crystalline magnetic nanoparticles at record levels of hysteretic heat dissipation in alternating magnetic fields. These nanoparticles can be functionalized with pharmacological payloads using thermally cleavable linkers and decorated with moieties targeting neuronal membranes. Upon magnetothermal activation, the nanoparticles release their payloads to locally evoke neural activity. Heat dissipated by the magnetic nanoparticles can also be applied to disrupt aggregates of amyloid beta, which may find future applications in the basic study of Alzheimer's disease. The magnetothermal approaches developed by the Bioelectronics Group have been further leveraged for cancer detection in Sangeeta Bhatia's laboratory. In addition to wireless magnetothermal approaches to neural and chemical manipulation, the group collaborated with Yoel Fink's team at RLE to develop fiber-based scaffolds for neural tissue regeneration and monitoring. Building on their prior work involving multifunctional fiber-based neural probes, they have demonstrated that fiber scaffolds can guide as well as stimulate nerve repair. Finally, the group made strides toward demonstrating the first chronic optoelectronic fiber-based interface with the spinal cord. By using stretchable elastomer fibers coated with micron-thick meshes of nanowires, they were able to demonstrate electrophysiological recording and optogenetic neuromodulation in the spinal cord of awake, freely moving mice, paving the way for future spinal neural prostheses.

Professor Lou Braida and the Sensory Communication Group investigated topics in three broad areas: hearing aids, tactile communication of speech, and auditory-tactile interaction. Work during the past year was focused on hearing aids. The long-term goal of the group's hearing aid research is to develop improved aids for people suffering from sensorineural hearing impairments and cochlear implants for the deaf. Efforts center on problems resulting from inadequate knowledge of the effects of various transformations of speech signals on speech reception by impaired listeners, specifically the fundamental limitations on the improvements in speech reception that can be achieved by processing speech. Key work during the past year focused on problems faced by hearing-impaired listeners in understanding speech in backgrounds of noise. Deterioration in speech intelligibility in noise is particularly acute for listeners with impaired hearing. In particular, studies indicate that hearing-impaired listeners derive less benefit than normal-hearing listeners in the presence of intermittent noises. This most likely accounts for the dissatisfaction many impaired listeners experience with hearing aids. The team is developing a signal-processing technique that seeks to improve speech comprehension in environments with intermittent noise such as in a restaurant. Results obtained with a real-time signal-processing system indicate that this technique improves the performance of hearing-impaired listeners in situations of fluctuating background noise, particularly noise with periodic gaps. In addition, the group has published results of efforts in the area of auditory-tactile integration; this work is concerned with the role of stimulating frequency (50 Hz and 250 Hz) on the effects of the phase at which the auditory and tactile components are presented. The findings indicate that integration at both frequencies is essentially phase independent, thus arguing for cross-modal integration at the level of the stimulus envelope rather than the temporal fine structure.

The research in Professor Dennis Freeman's group explores the cochlear mechanisms that underlie the extraordinary properties of our sense of hearing, focusing primarily on sensitivity to low-amplitude sounds and acute frequency selectivity, which are hallmarks of mammalian hearing. Work during the past year has focused on characterizing mechanisms in humans. It is well known that neural tuning is sharper in the human auditory system than in that of other mammals. However, the mechanisms underlying such a difference remain unclear. Sharp tuning in genetically modified mice has been attributed to decreases in the spread of excitation of tectorial membrane traveling waves. To test whether similar mechanisms are at play in humans, the group completed the first direct measurements of human tectorial membrane traveling waves. Interestingly, the material properties of human tectorial membranes are similar to those of other mammals. Therefore, the cochlear distances over which acoustic stimuli are coupled are also similar for humans and other mammals. The significant difference is in the cochlear map, which describes the relation between longitudinal cochlear position and the frequency that best stimulates that position. In comparison with other mammals, the human cochlea maps a smaller range of frequencies to each millimeter of cochlear length. Thus, although similar distances are coupled through the tectorial membrane in all mammals, a smaller range of frequencies are coupled in humans. This difference is sufficient to account for the sharper neural tuning seen in humans. These results could have applications to the clinical diagnosis and treatment of hearing disorders.

Professor James Fujimoto and the Biomedical Optical Imaging and Biophotonics Group perform research in biomedical optical imaging and optical coherence tomography (OCT). The group's research spans technology development, fundamental studies, and clinical applications. They have collaborations with investigators at the Harvard Medical School, the Boston Veterans Affairs (VA) Healthcare System, the Tufts University School of Medicine, Massachusetts General Hospital, the University of Pittsburgh School of Medicine, Oregon Health and Sciences University, and Erlangen University in Germany. The group performs studies in clinical ophthalmology at the New England Eye Center, New York University, and Oregon Health and Sciences University; gastroenterology and endoscopic studies at the Harvard Medical School and Boston VA Healthcare System; and pathology and breast cancer surgical studies at the Harvard Medical School and Beth Israel Deaconess Medical Center.

Professor Fujimoto's group and collaborators were responsible for the invention of optical coherence tomography in the early 1990s, as well as its commercialization by Carl Zeiss and its initial applications in ophthalmology. OCT has become a standard diagnostic procedure in ophthalmology, and an estimated 20 to 30 million ophthalmic OCT imaging procedures are performed worldwide every year. OCT is also an emerging imaging modality for intravascular and endoscopic imaging.

The group has developed a next-generation high-speed ophthalmic OCT imaging instrument that is in use at the New England Eye Center. The collaborative team is performing studies of structural and functional retinal imaging to investigate disease pathogenesis and treatment response in age-related macular degeneration, diabetic retinopathy, and glaucoma—all leading causes of blindness.

The group also developed a next-generation OCT endoscopic imaging system that is in use at the Boston VA Healthcare System. Studies in this area utilize high-speed imaging to generate high-resolution volumetric structural and functional data on upper and lower GI pathologies. Studies are ongoing to determine the ability of endoscopic 3D OCT to detect dysplasia in the upper GI tract as a means of guiding biopsies and assessing ablative therapies (e.g., radio frequency ablation) for the treatment of dysplasia and cancer.

Recently the group developed a nonlinear microscopy technology for imaging breast cancer surgical specimens. In a study with collaborators at the Beth Israel Deaconess Medical Center, they demonstrated that nonlinear microscopy can assess breast cancer pathology with sensitivity and specificity approaching that of standard histopathology. The group and collaborators recently designed and received institutional review board approval for a study investigating nonlinear microscopy as a means of performing real-time assessments of surgical margin status in breast cancer patients to reduce the rate of repeat surgeries. Study enrollment is expected to begin shortly.

Professor Martha Gray leads the Biomedical Technology Innovation Group. Her research program focuses on formalizing approaches that drive innovation to create impact, particularly in the context of predoctoral and postdoctoral research training. The group's highlights include the following.

The Catalyst Program celebrated five years of success with an increased pace and volume of innovation. The program opened new lines of work and attracted significant new funding (approximately $15 million) thanks to a $20 million investment by the Community of Madrid. The program's Team Fetal, whose aim is to assess placental function to determine the need for early delivery, received a multimillion-dollar grant from NIH. Team NeuroQWERTY was awarded a grant by the Michael J. Fox Foundation to support the further development of their technology to detect Parkinson's disease through natural interactions with a computer keyboard. Finally, Team Hydration received a point-of-care grant from NIH to develop a device that can measure hydration in vulnerable populations such as older people in care facilities, for whom dehydration can lead to reduced mental functioning and falls.

Piloted in 2014–2015 through MIT's Innovation Initiative, the MIT IMPACT Program was officially launched thanks to a five-year NIH grant. This career development program now runs two editions a year, with 24 participants each, and involves mentors from throughout the local biomedical community.

Another new program, IDEA² Global, provides biomedical innovators around the world with mentoring and connections to develop their project ideas and offers them the expertise to realize these ideas. IDEA² Global evolved from two prior programs, IDEA² at HST (Harvard-MIT Division of Health Sciences and Technology) and IDEA² Madrid, and was supported by corporate funding. There were about 50 applications for 15 slots offered to the 2016 class.

Professor Jongyoon Han leads the Micro/Nanofluidic BioMEMS Group. Their research focuses on molecular and cell separation and sorting technologies as well as novel uses of various types of ion-selective membranes.

Since 2010, Professor Han and his team have been investigating ion concentration polarization (ICP) desalination, which is a novel electrical desalination technique. In recent work, the team has elucidated the unique advantages of ICP desalination over conventional electrodialysis. For instance, the group discovered that ICP desalination involves a higher salt removal ratio than electrodialysis given the same operating current due to its unique unipolar ion conduction design. This can translate into up to 50% less energy consumption than electrodialysis if all other conditions remain equal. Results also showed that ICP desalination can be used to treat brine (wastewater that is saltier than seawater) more economically than available techniques. Brine wastewater treatment is gaining importance in conventional desalination, oil and gas, and mining industries, but currently the cost of treating (desalinating) brine is prohibitively high. The team hopes to further engineer the technique to be used for such challenging water treatment problems in the future. The team's research was supported by the Kuwait-MIT Center for Natural Resources and the Environment.

Professor Thomas Heldt directs the Integrative Neuromonitoring and Critical Care Informatics Group in RLE and the Institute for Medical Engineering and Science (IMES). Using physiologically based dynamic models, the group leverages multivariate bedside monitoring data—on the second to hour time scale—to understand the physiology of the injured brain, to improve diagnoses, and to accelerate treatment decisions for the critically ill. The group continues very strong collaborative ties with clinicians at Boston Children's Hospital, the Boston Medical Center, Massachusetts General Hospital, and the Beth Israel Deaconess Medical Center in the areas of neurocritical and neonatal critical care. Professor Heldt is currently serving as the lead of RLE's biomedical engineering and science theme.

A key research accomplishment over the past year has been further improvements in the group's model-based noninvasive and patient-specific approach to intracranial pressure estimation. The results of these efforts have been published and were presented at this year's 16th International Conference on Intracranial Pressure and Neuromonitoring. The conference was held on the MIT campus and brought together over 300 attendees from

21 countries to discuss recent research and clinical progress in monitoring patients with critical neurological conditions. Professor Heldt served as the conference chair, with strong support from the IMES and RLE administrations.

Other key group accomplishments include the graduations of Max Dunitz and Jonathan Matthews (MEng), the awarding of the David Adler MEng Thesis Prize in Electrical Engineering to Dunitz, and the awarding of the Louis D. Smullin ('39) Excellence in Teaching Award to Professor Heldt.

Professor Timothy Lu's Synthetic Biology Group seeks to construct and re-encode biological systems from the ground up. Over the past year, the Lu group published several major advances in the field.

Discovering gene and drug combinations that modulate biological phenotypes and human diseases requires scalable, multiplexed screening technologies. The Lu group developed the CombiGEM (combinatorial genetics en masse) technology, which assembles high-order barcoded combinatorial genetic libraries that are quantifiable with high-throughput sequencing. The group found certain combinations of human micro-RNA precursors that synergistically re-sensitize drug-resistant cancer cells to chemotherapy and/or inhibit cancer cell proliferation.

Combining CombiGEM with CRISPR-Cas9 technology to make genetic libraries targeting specific genomic loci, the Lu group observed synergistic anti-proliferative effects against ovarian cancer cells. CombiGEM-CRISPR may identify disease-relevant genetic combinations and modulate disease phenotypes.

The Lu group modified bacteriophage (phage) host ranges by engineering phage genomes in *Saccharomyces cerevisiae*. They found that swapping phage tail components caused phage scaffolds to be redirected: synthetic phages killed targeted bacteria and removed bacteria from multi-species bacterial communities. In addition, the group characterized a *Pseudomonas aeruginosa* phage isolated from hospital sewage as part of the Myoviridae family and *Pbunalikevirus* genus.

To map gene expression to metabolic outputs in *Corynebacterium glutamicum*, an industrial producer of amino acids, the Lu group applied CRISPR interference and assessed the effects of gene repression by deactivated Cas9 on amino acid titers. The results indicated that CRISPR interference could serve to remodel metabolic pathways.

Synthetic DNA can store non-biological information. The Lu group, exploring the communication of short messages fragmented across multiple distinct DNA molecules, developed three tools for widespread communicating via DNA molecules: iKeys, converting plaintext into DNA for data encoding; Multiplexed Sequence Encoding (MuSE), concealing messages for data transfer; and chromatogram patterning for data extraction.

To track and record molecular events in vivo, the Lu group constructed an analog memory device that records molecular stimuli as DNA mutations in human cells.

Memory units encoded in human cells and implanted into mice recorded acute inflammation over time. The Mammalian Synthetic Cellular Recorder Integrating Biological Events (mSCRIBE) tool can enable investigations of mammalian cell biology in vivo and in situ.

Living cells compute environmental signals via analogue- and digital-like signal processing, yielding complex developmental programs, context-dependent behaviors, and homeostatic activities. The Lu group integrated analogue and digital computation to implement synthetic genetic programs in living cells, developing a hybrid computational paradigm to digitize analogue inputs.

In 2015–2016, the work of principal research scientist Stefanie Shattuck-Hufnagel and her group focused on speech processing (production and perception) among both adults and children; specifically, they tested the hypothesis that individual acoustic cues to the feature contrasts that define the sounds of words form a separate level of cognitive representation (in addition to the traditionally defined linguistic constituents of morphemes, phonemes, and their defining features). A study of phonetic variations of /t/ and /d/ in the speech of two- and three-year-old children and their adult caretakers showed that children seldom produce the reduced forms (flaps, glottalization) that adults habitually do, instead producing canonical versions of these stop consonants (complete with full closure, pressure buildup behind the constriction, and a fricated noise burst at release). This suggests that children do not imitate the sounds of the words they hear but, rather, produce word forms using their own individual feature cues, based on their knowledge of adult phonological forms. These findings have implications for modeling typical phonological development in children because they imply that children first produce canonical word forms with the full range of acoustic cues to the features and only later learn how to produce the reduced context-specific forms of adult speech. Such a model differs sharply from current proposals according to which children begin by reproducing the highly variable reduced forms that they hear from adults and only later master the underlying phonological category that links them to a sequence of abstract phonemes. If confirmed by further investigations, the study's implications for clinical intervention in children with phonological delay or disruption will be profound.

Additional studies of phonological development revealed that children produce different cues than adults to the voicing contrast in coda consonants as well as fewer speech-accompanying gestures. Furthermore, there is evidence that children produce the phrase-medial plural morpheme *-s* more reliably when it is followed by a vowel (as in *Dogs eat*) than when it is followed by more complex structures such as an initial consonant (*Dogs bark*) or a two-syllable word (*Dogs arrive*). These findings provide additional evidence that children do not simply imitate the speech and speech-accompanying gestures that they hear and see around them, but rather that they learn the contrastive categories of the ambient language and signal them in ways that are consistent with their own planning and articulatory capacities.

Additional studies concerning the control of timing of speech and other motor activities revealed that repeated tokens of simple tapping patterns produced by adults showed a tendency to leave a multiple of the beat duration between repetitions, suggesting that participants generated global planning frameworks rather than planning one movement at a time; participants repeating groups of manual zig-zag motions did not show the same kind of group-final duration lengthening seen in speech; and listeners showed various types of memory (i.e., both categorical and continuous valued) for the pitch characteristics of a spoken utterance, illustrating the capacity to process a given characteristic of the acoustic speech signal in several different ways.

Professor Collin Stultz and the Computational Biophysics Group focused on developing computational tools that improve our understanding of fundamental biochemical processes that play a role in human disease, and identifying patients at increased risk of death after adverse cardiovascular events (e.g., heart attacks, strokes).

The group's overall goal is to develop an improved understanding of disease processes at the molecular level and use these insights to build novel therapies. Their approach to achieving this goal involves both building computational/theoretical models and conducting biochemical experiments that are designed to test and refine these models. They have developed a deep interest in understanding the structure of intrinsically disordered proteins that play a role in neurodegenerative disorders. The objective of these studies is to use this improved understanding to design molecules that prevent the formation of neurotoxic aggregates from these proteins. The group has developed a tool (made generally available online) for building models of disordered proteins. Structural models for these proteins are an essential step toward understanding why certain proteins have a preference for forming neurotoxic aggregates in the brains of patients with neurodegenerative disorders. Over the past year, the group has also developed a method for quantifying protein disorders from small-angle X-ray scattering (SAXS) experiments. This method is one of the only generally available means of quantifying protein disorders from SAXS profiles. As a result of its contributions to this area over the past several years, the group was invited to write a review article for the *Journal of Biological Chemistry*.

Over the past five years, the group has been actively working toward generating computational methods that will identify patients who are at high risk of death after presenting with acute coronary syndrome, a process that leads to heart muscle dysfunction and/or death. This year they developed a new approach that analyzes electrocardiogram (ECG) signals in a manner that leads to improved risk stratification metrics. The standard ECG represents cardiac activity as a function of time. The group's new approach transforms standard analyses of the ECG signal from the time domain to a "beat-space" domain. A power spectral analysis in the beat-space domain leads to cycles per beat metrics rather than the traditional time-domain Hz metric (cycles per second).

The Computational Physiology and Clinical Inference Group, directed by Professor George Verghese, is focused on bedside informatics using physiologically based dynamic models to interpret multivariate monitoring data collected in settings ranging from acute care to home monitoring. The group interacts closely with Professor Thomas Heldt's Integrative Neuromonitoring and Critical Care Informatics Group. Several clinical collaborators also participate in their research.

An important direction of research in the group is aimed at more extensive and refined use of time-based capnography, which records partial CO_2 pressure as a function of time in exhaled breath. Capnographs are ubiquitous in hospital settings and ambulance systems, but only a fraction of the information they provide is currently extracted and used. This research is being carried out with the close involvement of Dr. Baruch Krauss at Boston Children's Hospital and his clinical collaborators in various hospitals (in Philadelphia, Vancouver, and Trieste), who have collected valuable original data for the studies. A paper that appeared in *IEEE Transactions on Biomedical Engineering* in December 2015 presented part of the doctoral thesis work of Rebecca Mieloszyk under the co-supervision of Professors Heldt and Verghese. The framework described in the paper comprises automated tools for preprocessing the capnogram (collected in a noninvasive and effort-independent manner during a few minutes of normal breathing) and extracting physiologically relevant features, followed by machine learning algorithms that classify the capnogram. The approach is able to distinguish, with good accuracy, patients with chronic obstructive pulmonary disease (COPD) from patients with congestive heart failure, even though these two groups can present to an emergency department with very similar symptoms; also, it can distinguish COPD patients from healthy subjects with very high accuracy. The work reported in the paper is currently being evaluated in an emergency medical service/ambulance service in Richmond, VA. Research is under way to incorporate mechanistic models that explain the capnogram and to extend the approach to asthma monitoring and severity assessment as well as procedural sedation. Two related patent applications have been filed.

In his MEng thesis Max Dunitz, also co-supervised by Professors Heldt and Verghese, used machine learning methods to predict high lactate levels (a marker for septic shock) from standard monitoring data collected in intensive care units. As noted above, this scholarly and ambitious thesis won the David Adler prize. A related patent application has been filed.

Professor Verghese's textbook with Professor Alan Oppenheim, *Signals, Systems and Inference* (Pearson), which was published in a US edition in April 2015, has been adapted by the authors into an international edition that will appear this year. They have also prepared a solutions manual for instructors who adopt the textbook for their classes.

Professor Joel Voldman's research interests are focused on bioMEMS, applying microfabrication technology to illuminate biological systems ranging from point-of-care diagnostics to fundamental cell biology and applied neuroengineering. Professor Voldman and the Biological Microtechnology and BioMEMS Group have been working on two areas this past year. The first, developing microsystems to manipulate cells for basic and applied cell biology, includes devices for studying immune cells and neurons. The group reported on a microfluidic device able to pair immune cells with cancer cells and then study their interactions over time as the immune response develops, allowing the first investigation into the immune cell response in terms of whether to kill the cancer cells or release chemicals to recruit other cells. The second area of research focused on microsystems for human health, with work on point-of-care diagnostics and cell analysis tools. In this area, Professor Voldman reported on the first microfluidic device able to sort cells based on their acoustic properties, enabling assessments of the density and compressibility of large numbers of single cells.

Dr. Mehmet Fatih Yanik's High-Throughput Neurotechnology Group is developing high-throughput, high-content technologies for investigating the complex development, function, reprogramming, degeneration, and regeneration of the nervous system. They employ a variety of techniques including micromanipulation, microfluidics, ultra-fast optics, advanced microscopy, quantum physics, genetics, and biochemistry. They also work with a variety of organisms and preparations ranging from *Caenorhabditis elegans*, zebrafish, and primary rodent and human brain tissues to human stem cell–derived neurons.

Nanoscale Materials, Devices, and Systems

This theme comprises research in fabricating surface structures at nanoscales, nanomagnetics and microphotonics, periodic structures, superconductive materials, and carbon nanotubes.

Professor Karl Berggren's research group develops nanofabrication methods for applications in quantum technologies and nanotechnologies. The main focus is on superconducting nanotechnologies for radiation detectors, quantum circuits, and superconducting nanoelectronics. The group also investigates fundamental interactions of electrons, ions, and photons with matter for applications in lithography, microscopy, and nanofabrication.

Professor Berggren's group recently showed that the collective electron excitations known as volume plasmons are key intermediates in the delocalized transfer of energy from focused electron beams to matter. The group demonstrated that these volume plasmons limit the resolution of electron-beam lithography on the sub-10-nm length scale. Since volume plasmons decay in materials over distances on the order of 10 nm, the group recently investigated the behavior of such plasmons in strongly confined materials with reduced dimensions.

During the past year, Professor Berggren and his team used electron energy-loss spectroscopy to map the complete plasmonic spectrum of aluminum nanodisks (with diameters ranging from 3 nm to 120 nm) fabricated by high-resolution electron-beam lithography. Their nanopatterning approach allowed them to produce localized surface plasmon resonances across a wide spectral range spanning 2 to 8 eV, opening up opportunities to use such materials for surface-enhanced Raman spectroscopy in the ultraviolet. Electromagnetic simulations support the existence of multipolar as well as centrosymmetric breathing surface plasmon modes depending on the location of the electron-beam excitation. The group also developed an approach using nanolithography that is capable of attosecond control over the lifetime of volume plasmons in these nanodisks. The precise measurement of volume plasmon lifetime may provide an opportunity to probe and control the DC electrical conductivity of highly confined metallic nanostructures with high spatial resolution. As part of this study, the group showed the strong influence of the nanodisk boundary in determining both the energy and lifetime of surface plasmons and volume plasmons locally across individual aluminum nanodisks and compared these observations with similar effects produced by scaling the nanodisk diameter. Their study will support the development of nano-optical sensors operating in the ultraviolet and improve our fundamental understanding of collective electron behavior in strongly confined metal nanoparticles.

Professor Dirk Englund leads the Quantum Photonics Laboratory, focusing on semiconductor quantum technologies for controlling quantum states in photons and spins to address problems in communication, computation, and metrology. Major research accomplishments include the first scalable process for integrating solid state spin quantum memories into photonic circuits, a theoretical protocol for all-optical quantum repeater nodes to extend quantum secure communications from metropolitan areas to global reach, and demonstration of electrical modulation of fluorescent nanodiamonds toward optical neuronal voltage sensing. Professor Englund is one of the principal investigators of an Air Force Office of Scientific Research Multidisciplinary University Initiative program ("Optimal Measurements for Scalable Quantum Technologies") and a new NSF Emerging Frontiers in Research and Innovation program on quantum repeaters, both of which include principal investigators from MIT and collaborators from Harvard, Yale, and the University of Maryland.

Fibers are among the earliest forms of human expression, yet surprisingly have remained unchanged from ancient to modern times. Can fibers become highly functional devices? Professor Yoel Fink's research focuses on extending the frontiers of fiber materials from optical transmission to encompass electronic, optoelectronic, and even acoustic properties. In recent years, his group has pioneered a new approach to fibers that are made of a multiplicity of disparate materials arranged in elaborate geometries with features down to 10 nm. Two complementary strategies toward realizing sophisticated functions are utilized: on the single-fiber level, the integration of a multiplicity of functional components into one fiber, and, on the multiple-fiber level, the assembly of large-scale fiber arrays and fabrics. These multi-material fibers offer unprecedented control over material properties and function on length scales spanning the nanometer to kilometer range. A few highlights of this year's activities are as follows.

Professor Fink led a $330 million winning proposal for the formation of the latest US manufacturing innovation institute. On April 1, Secretary of Defense Ash Carter announced that the Advanced Functional Fabrics of America (AFFOA) team won the national competition for federal funding to create the new institute. AFFOA is dedicated to the mission of enabling a manufacturing-based revolution by transforming traditional fibers, yarns, and fabrics into highly sophisticated and networked devices, systems, and products while strengthening the domestic supply chain in this area. Its broad-based support from government, industry, and academia is a testament to the institute's vision and goals. In addition, Fink's work formed the basis for an NSF Materials Research Science and Engineering Center interdisciplinary research group focusing on fiber fluid instabilities. Also participating in this work were RLE principal investigators Polina Anikeeva, John Joannopoulos, Steven Johnson, and Marin Soljačić.

Fink and his group submitted a paper to *Nature Communications* describing how fibers with electronic and photonic properties are essential building blocks for functional fabrics with system-level attributes. The scalability of the thermal fiber approach offers access to large device quantities while constraining the devices to be translationally symmetric. Lifting this symmetry to create discrete devices will increase their utility. The team drew from a macroscopic preform fibers that had three parallel internal non-contacting continuous domains. They then heated the fibers and generated capillary fluid instability, which led to the selective transformation of the cylindrical semiconducting domain into discrete spheres without changing the conductive domains. The cylindrical-to-spherical expansion bridges the continuous conducting buses to create approximately 10^4 self-assembled, electrically contacted, and entirely packaged discrete spherical devices per meter of fiber. The photodetection and Mie resonance dependent response are measured by illuminating the fiber while connecting its ends to an electrical readout.

The research of Professor Jing Kong and the Nano-Materials and Electronics Group focuses on the challenge of developing the chemical vapor deposition synthesis routes of various 2D materials, characterizing their structures and properties and assessing their applications. They are designing new strategies to make graphene, MoS2, and other novel 2D materials with desired physical and chemical qualities. Their in-depth understanding of how to make those materials enables them to develop new architectures for high-performance electronics and energy conversion.

The group's recent research focus has been on two areas: large-area chemical vapor deposition synthesis of 2D materials and development of highly porous low-density, high-surface-area aerogel materials.

The Kong group had several interesting results over the past year. They successfully developed the synthesis route for metallic-phase MoTe2, showing the lowest sheet resistance value reported so far in the literature. The team also developed a room-temperature transfer technique to allow graphene to be transferred as a top electrode for organic solar cell devices; they subsequently developed flexible visibly transparent solar cells using graphene top and bottom electrodes, which has a great deal of potential for ubiquitous energy harvesting. By further investigating graphene transfer details, they also developed a strategy to successfully transfer graphene onto rough substrates, enabling the fabrication of much more complex structures with graphene and other 2D materials. In addition, they continued their graphene strain sensor work and improved the sensitivity of their sensor so that it is more suitable for future applications.

Professor Yang Shao-Horn's research programs are centered on understanding the electronic structures of surfaces, with emphasis on metal oxides; searching for descriptors of catalytic activity, surface/interface reactivity, and ion transport; and applying fundamental understanding to design materials for oxygen electrocatalysis, CO_2 reduction, ion intercalation, and ion conductors in electrochemical-photoelectrochemical conversion and storage, including lithium-ion batteries, flow batteries, metal-air batteries, proton exchange membrane and solid oxide fuel cells.

Professor Shao-Horn's group recently observed strong structural oscillations of $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) in the presence of both H_2O vapor and electron irradiation using environmental transmission electron microscopy. These oscillations are related to the formation and collapse of gaseous bubbles. Electron energy loss spectroscopy provides direct evidence of O_2 formation in these bubbles due to the incorporation of H_2O into BSCF. $SrCoO_{3-\delta}$ was found to exhibit small oscillations, while none were observed for $La_{0.5}Sr_{0.5}CoO_{3-\delta}$ or $LaCoO_3$. The structural oscillations of BSCF can be attributed to the fact that its oxygen 2p-band center is close to the Fermi level, which leads to a low-energy penalty for oxygen vacancy formation, high ion mobility, and high water uptake. This work provides surprising insights into the interaction between water and oxides under electron beam irradiation. Understanding interactions between water and oxides is critical for many technological applications, including energy storage, surface wetting/self-cleaning, photocatalysis, and sensors.

Understanding and controlling the kinetics of O_2 reduction in the presence of Li^+-containing aprotic solvents, to either Li^+-O_2^- via one-electron reduction or Li_2O_2 via two-electron reduction, is instrumental in enhancing the discharge voltage and capacity of aprotic Li-O_2 batteries. Standard potentials of O_2/Li^+-O_2^- and O_2/O_2^- were experimentally measured and computed using a mixed cluster-continuum model of ion solvation. Increasing combined solvation of Li^+ and O_2^- was found to lower the coupling of Li^+-O_2^- and the difference between O_2/Li^+-O_2^- and O_2/O_2^- potentials. The solvation energy of Li^+ trended according to donor number and varied to a greater degree than that of O_2^- ions, explaining the previously reported correlation between Li^+-O_2^- solubility and donor number. These results highlight the importance of the interplay between ion-solvent and ion-ion interactions for manipulating the energetics of intermediate species produced in aprotic metal-oxygen batteries.

Photonic Materials, Devices, and Systems

This theme includes significant efforts in integrated photonic devices, modules and systems for applications in communications and sensing, femtosecond optics, laser technologies, photonic bandgap fibers and devices, materials fabrication, laser medicine and medical imaging, and millimeter-wave and terahertz (THz) devices.

Professor Marc Baldo is the director of the DoE-sponsored Center for Excitonics, an Energy Frontier Research Center whose principal mission is to supersede traditional electronics with devices that use excitons to mediate the flow of energy. Whereas the former rely on expensive and energy-intensive fabrication processes, the latter are far more suitable for the large-scale production that would be needed to generate sufficient solar cells to have a significant impact on the world energy supply. Professor Baldo's own research program currently centers on solar cells, light-emitting devices, and spintronic switches. A key research accomplishment of the past year was his group's demonstration, together with Vladimir Bulović in EECS and Moungi Bawendi and Troy Van Voorhis in the Department of Chemistry, of the first conversion of low-intensity infrared light to visible light in a solid state structure. Another key result was the demonstration of computationally designed materials for organic light-emitting devices using an algorithm guided by artificial intelligence. This approach promises to transform the traditional synthesis-heavy iteration cycle used in industry. The work was performed in collaboration with Alan Aspuru-Guzik and Ryan Williams from Harvard. Finally, together with Adam Willard and Troy Van Voorhis in Chemistry and Vladimir

Bulović in EECS, the group resolved a key question in the operation of organic solar cells: how do these devices generate current given that the charges are electrostatically bound together immediately after formation? The answer was obtained from direct imaging of these bound charge states. They were observed to diffuse across tens of nanometers, which is sufficient for location of sites capable of charge generation within the disordered energetic landscape.

Professor Vladimir Bulović, associate dean for innovation in the MIT School of Engineering and Fariborz Maseeh (1990) Professor of Emerging Technology, co-directs the MIT Innovation Initiative and is leading the design and construction of MIT.nano, the Institute's new nano-fabrication, nano-characterization, and prototyping facility. Also, he leads the Organic and Nanostructured Electronics Laboratory and co-directs the MIT-Eni Solar Frontiers Center and the MITEI Low-Carbon Energy Center on Solar Technologies. Professor Bulović's research interests include studies of physical properties of organic and organic/inorganic nanocrystal composite thin films and structures and the development of novel nanostructured optoelectronic devices.

Over the past year Professor Bulović, in collaboration with the groups of Professor Jeffrey Lang (EECS) and Professor Tim Swager (Chemistry), published a series of papers that demonstrated a new nano-electromechanical (NEM) structure they called the squeezable switch (or "squitch"), which for the first time operates at an applied voltage below 1 V by mechanically deforming a molecular film between contact electrodes. The abrupt switching behavior and near-zero leakage current of NEM switches are advantageous properties through which these structures can outperform conventional semiconductor electrical switches. Prior to this demonstration, however, typical NEM structures required high actuation voltages and typically prematurely failed through the permanent adhesion (defined as stiction) of device components. To overcome these challenges, Bulović and colleagues designed the squitch to electromechanically modulate the tunneling current through a nanometer-scale gap defined by an organic molecular film sandwiched between two electrodes. When voltage is applied across the electrodes, the generated electrostatic force compresses the sandwiched molecular layer, reducing the tunneling gap and causing an exponential increase in the current through the device. The presence of the molecular layer avoids direct contact of the electrodes during the switching process. Furthermore, as the layer is compressed, the increasing surface adhesion forces are balanced by the elastic restoring force of the deformed molecules, which can promote zero net stiction and recoverable switching. The team demonstrated the potential of optimizing the squitch design to enable large on-off ratios beyond six orders of magnitude with operation in the sub–1 V regime and with nanosecond switching times. With optimization of device design and material engineering, squitches can give rise to a broad range of low-power electronic applications previously unattainable with NEM technologies.

Professor Peter Hagelstein's group has been working on theoretical and experimental studies related to condensed matter nuclear science (including cold fusion and related anomalies). One of the group's most interesting results stems from a theoretical project involving the development of a new global statistical mechanics model for hydrogen in palladium. In earlier models, hydrogen was presumed to occupy octahedral sites;

in the Hagelstein group model, hydrogen is also allowed to occupy tetrahedral sites. The group was able to develop good fits to the isotherms of the phase diagram with model parameters consistent with a physical model (as opposed to a mathematical fit unconnected to the physical system). This approach has applications for PdD, NiH, NiD, and other FCC metal hydrides. The model is also useful for simulations of electrochemical loading and the development of statistical mechanics models for superabundant vacancy phases.

A different theoretical project involving the systematic development of models for both nonrelativistic and relativistic composite quantum mechanical systems led to another interesting result. The notion of a quantum mechanical composite is fundamental to atomic, molecular, nuclear, and particle physics; it is therefore astonishing that a systematic review of quantum composites has not previously been undertaken. The Hagelstein group conducted a lengthy review of quantum composites in which they described models for elementary particles that have been adapted to describe composite particles (the most widely used is the Dirac equation to describe protons and neutrons); in addition, they described a derivation for multi-particle nonrelativistic composites with external field coupling and derived several models for the multi-particle relativistic case, including different quasi-relativistic versions. These models included external field coupling and, in the relativistic cases, coupling with the center of mass momentum.

These models are important for several reasons. For example, relativistic corrections are widely used to correct nonrelativistic composite models; however, there are many subtle errors in the literature that become obvious in a systematic treatment. The Hagelstein group has been interested in the coupling between internal nuclear degrees of freedom and lattice degrees of freedom in the case of a nucleus embedded in a lattice. The previous focus has been on the weak second-order coupling due to electric and magnetic interactions, and the coupling between the center of mass momentum and internal degrees of freedom has generally been ignored. In free space these interactions can be rotated out, so they are almost never considered; however, if there are interactions with other particles, the rotation is not clean. The group has conjectured that this kind of coupling is responsible for the anomalies observed in condensed matter nuclear science, since the coupling is between composite motion and internal transitions. Now there is a consistent set of interactions to work with, interactions that are derivable from many-particle Dirac models, from Poincare invariant models, and from field theory.

The coupling under discussion is a subtle kind of phonon-nuclear coupling that, within the scientific community, is not believed to exist. One conventional application of this coupling is to nuclear-level splitting in certain homonuclear diatomic molecules with identical isotopes that involve a low-energy excited state (an application the group is currently studying). It may be that the more important application of this "new" phonon-nuclear coupling is to anomalies more generally in condensed matter nuclear science (e.g., excess heat production, tritium generation, and collimated X-ray radiation).

The group has also engaged in preliminary efforts to confirm the "Kornilova experiment," in which a steel plate was placed next to a water jet and collimated X-ray emission between 1 and 2 keV was observed. The Hagelstein group is interested in this experiment in part because it is closely related to the Karabut glow discharge experiment in which reproducible collimated X-ray emission between 1 and 2 keV was reported over a 10-year study that involved four different primary diagnostics. The group interpreted this experiment's results as being due to anomalous up-conversion of many vibrational quanta to produce nuclear excitation. They conjectured that the low-energy 14.4 keV transition in Fe-57 is responsible for the up-conversion and that the emission is due to the 1565 eV transition of a small number of Hg-201 nuclei present as a surface contaminant.

The group carried out some experiments at MIT with a water jet in order to learn more about this experiment and to see whether they could confirm the results. They found a number of artifacts in their version of the experiment but were not able to reproduce the results. They subsequently found a number of problems with their version of the experiment, motivating them to consider a new study this coming winter.

One problem with the Kornilova experiment is that it is uncontrolled. For example, if vibrations are being up-converted, it is unknown which vibrational modes are excited, how much excitation is present, or what kinds of modes and what frequencies are involved. As a result, the group developed a facility in which they can excite compressional, transverse, and drum head vibrational modes as they choose, at amplitudes they can set. They also developed and/or acquired detectors that can be used to measure mode excitation and detect X-ray and other emissions (in order to test claims made by other researchers regarding charge emissions, neutron emissions, and gamma emissions). The expectation is to test samples systematically this fall and winter.

The group developed a sensitive calorimeter that can be used to test for anomalous excess heat production in solid state cold fusion devices. Tests have begun with the goal of understanding whether thermal power or energy production is present in cold fusion devices.

Professor Qing Hu studies terahertz quantum cascade lasers and electronics and sensing and real-time THz imaging using quantum cascade lasers and focal-plane cameras. His group has achieved many world records in terms of the performance of their THz quantum cascade lasers, including but not limited to the highest operating temperatures in the pulsed mode and the continuous wave mode. They have performed real-time THz imaging at a video rate of approximately 20 frames per second. In addition, they have developed a novel tuning mechanism that is qualitatively different from all other tunable lasers and have achieved continuous tuning over a broad frequency range. More recently, they have developed the first THz laser frequency combs. These are experiments with the potential to lead to improvements in sensing, imaging, and high-bandwidth communications.

Professor Erich Ippen's research is directed toward advances in ultra-fast and nonlinear optics and integrated photonics. His group's successes in advancing optical clock and optical arbitrary waveform technologies with fiber lasers have led to new interests in more compact and integrated femtosecond lasers for sampling and timing applications. Efforts to pursue these interests on silicon nanophotonic platforms are being carried out in collaboration with Professors Michael Watts and Franz Kaertner. Recent progress includes demonstrations of integrated nonlinear femtosecond pulse shapers, octave-spanning continuum generation and second-harmonic generation in silicon waveguides, and integrated erbium-doped and thullium-doped waveguide lasers.

Work on optical combs has been synergistic with research in the Center for Ultracold Atoms. Femtosecond fiber and waveguide laser work, in collaboration with Professor Kaertner, is motivated by the prospects of precision on-chip signal processing for microwave applications and free electron laser facilities. Studies and demonstrations of silicon nanophotonic circuits are of general importance to advances in on-chip photonic communication and control as well as clock and comb miniaturization, and they are synergistic with the research of Professors Watts and Kaertner.

Professors John Joannopoulos and Marin Soljačić work together as a team in the area of nanophotonics. They are enthusiastic about their recent work on shrinking light to allow forbidden transitions on the atomic scale. In this work, they have shown that plasmons in 2D materials allow optical access to atomic transitions that were once considered inaccessible: multiplasmon spontaneous emission, singlet-triplet transitions, and very-high-order multipolar transitions were observed to occur on exceptionally short time scales. These transitions occur because the plasmons in 2D materials are extremely spatially confined.

The theory of light-matter interactions (quantum electrodynamics) is a great success in physics, leading to countless applications with broad impact such as lasers, atomic clocks, spectroscopy, LEDs, and many others. However, to this day, the use of light-matter interactions suffers from crucial constraints: most light-matter interaction processes are "forbidden" by electronic selection rules, limiting the number of accessible transitions. In their work, Joannopoulos and Soljačić have demonstrated that these constraints can be lifted using the strongly confined electromagnetic waves associated with polaritons in 2D materials. For example, they showed that transitions normally occurring over extraordinarily long periods can be made to happen within nanoseconds. Their study will serve as the foundation for the next generation of research on light-matter interactions.

From the standpoint of fundamental science, this effort lays the groundwork for a field that just a few years ago was completely unimaginable and until now was completely unexplored. Thus, Joannopoulos and Soljačić are confident that this work will lead to further theoretical and experimental breakthroughs in all fields involving study of light-matter interactions, including photonics, chemistry, optoelectronics, and atomic, molecular, and optical physics. From a technological point of view, the study has potential applications across multiple disciplines since it enables the full use of the periodic table for optical applications. Examples include multiplex spectroscopy and sensing, ultra-thin solar cells, new classes of materials to absorb solar energy, organic light-emitting devices with higher efficiencies, and reliable entangled photon sources for quantum protocols.

Professor Steven Johnson leads the Nanostructures and Computation Group. His research focuses on two areas: the influence of complex geometries, particularly at the nanoscale, on solutions to partial differential equations, especially for wave phenomena and electromagnetism, and high-performance computation including fast Fourier transforms, solvers for numerical electromagnetism, and large-scale optimization.

In the past year, Professor Johnson's group developed the first scalable 3D solver for above-threshold micro-lasers, and the group has exploited this work to obtain a purely analytical generalization of laser linewidth theory (in collaboration with Professor Douglas Stone at Yale). With Professor Alejandro Rodriguez at Princeton, the Johnson group developed the first theory of nonlinear thermal radiators, showing for the first time how the blackbody limit could be exceeded in the far field by a surface at a positive temperature (i.e., not a laser). In work with Professor Soljačić, they used numerical optimization to design new materials for "structural color" (color from geometry rather than pigment) that is both narrow bandwidth and angle independent.

On the computational front, the Johnson group published several efficient new algorithms for boundary-element methods in electromagnetism (in collaboration with Professor White). In addition, they demonstrated the first fully three-dimensional topology optimization of photonic crystals (discovering new bandgap structures and bounding the attainable performance for different materials).

Professor Franz Kaertner's research focuses on the study of attosecond science and single- to sub-cycle pulse generation in the mid- to long-wavelength infrared, 2-10 micron wavelength, via parametric amplification. In a collaboration with Professor Watts's Photonic Microsystems Group, Kaertner is attempting to integrate a femtosecond laser on a CMOS (complementary metal-oxide-semiconductor) chip in a fully 3D photonic-electronic integrated platform.

The Kaertner group has greatly refined its first observation of sub-cycle optical field emissions from a nanoplasmonic field emitter array at room temperature and within ambient conditions by detecting the carrier-envelope phase sensitivity of the emitter current as a function of carrier envelope phase from a mode-locked laser. The device, as is, can be used and further optimized towards a carrier-envelope phase detector. A nano-emitter array that can emit electrons via optical tunneling within an optical cycle can serve in principle as a modulated electron beam source for future coherent X-ray sources. This has the potential to perform fundamental attosecond science with chip scale devices.

The group has further pushed sub-cycle pulse generation into the 2- to 10-micron range using parametric amplification in novel nonlinear optical materials such as zinc-germanium-phosphate and cadmium-silicon-phosphate. Combining the signal and idler output from a 2-micron pumped optical parametric amplifier resulted in continuous spectral coverage from 2 to 10 microns and a sub-cycle pulse. Such pulses can be used to study strong-field physics effects in solids and gases as well as direct charged particle acceleration.

Together with Professor Watts's team, the group has made much progress in fabricating a complete femtosecond laser on a silicon photonics platform. Over the last year the first completely integrated devices have been fabricated, and all components seem to work up to the appropriate amplifying medium.

Professor Leslie Kolodziejski is collaborating with Professors Watts, Kaertner, and Ippen on creating an on-chip synthesizer. The proposed synthesizer uses an integrated mode-locked laser whose spectrum is broadened to an octave with an on-chip waveguide-based supercontinuum generator structure. Part of the resulting comb is frequency doubled via an integrated electrical-field-induced second harmonic generator doubler. Integrated germanium photodiodes are then used to detect and lock the repetition rate and the carrier envelope offset of the integrated mode-locked laser. Efforts are also continuing on the fabrication of laser gain media. The material of interest for the lasers in this project is rare-earth doped aluminum oxide due to its reliable sputtering process as well as its consistent and appropriate refractive index. The dopant used for lasers around 1.5 µm is erbium because of its commonly known gain bandwidth in the 1,530-nm to 1,560-nm communication band. However, due to the absorption of silicon at short wavelengths, erbium mode-locked lasers are not suitable for this application. To this end, thulium has been inspected as a dopant in the aluminum oxide medium for lasers around the 1.9-µm wavelength range. Continuous wave lasers have already been demonstrated in the project. Efforts now include the design and measurement of thulium-doped mode-locked lasers as well as testing of numerous passive optical components in the synthesizer circuit (e.g., various reflectors, filters, and splitters).

Professor Rajeev Ram and the Physical Optics and Electronics Group pursue investigations in two major thrusts: integrated photonics and electron transport in semiconductors. The group's current work focuses on unconventional classical and quantum CMOS computing, microsystems for the measurement and control of cellular metabolism, and thermodynamic limits of photonics.

Professor Ram and his team reported the first photodetector and the first optical interconnect in true CMOS with intimate integration of photonics and high-performance electronics. Also, Ram and has group presented a communication link using a thermal energy harvesting LED where the photonics consumed only 15 fJ per bit of energy. A roadmap for achieving the lower limit to energy consumption for communications (as dictated by the Shannon limit) using such a source was developed. Finally, the first results demonstrating microfluidic control of synthetic gene circuits were presented. This synthetic biology and microfluidics platform was used to demonstrate on-demand, switchable production of two proteins.

Professor Michael Watts and his Photonic Microsystems Group focus on 3D integration of silicon photonics with CMOS electronics and on-chip lasers for a variety of applications, including ultra-low-power wavelength division multiplexed optical communications, optical phased arrays, optical beam steering, low-phase-noise optical-microwave oscillators and microwave signal generation. Professor Watts's group has demonstrated the largest optical phased array ever produced, at 4,096 elements, projecting the MIT logo in the far field. Building on this demonstration, Professor

Watts has applied these results to chip-based LIDAR (light detection and ranging) technologies, achieving the largest scan angle of any chip-based optical phased array at 51 degrees. Professor Watts and his group also demonstrated a new record in low-power silicon modulators, achieving less than 1 fJ per bit in modulators running at 25 Gb per second in the world's first 300-mm silicon photonics platform. Additionally, combining ultra-low-power silicon modulators with 3D wafer CMOS integration, the group demonstrated the world's lowest power communication link at just 250 fJ per bit, a result that is sure to impact low-power communication links in future high-performance data centers.

Quantum Computation and Communication

This area of emphasis features efforts in quantum information processing and transmission, with extensive new initiatives in quantum computation, superconducting circuits, and understanding and exploiting quantum teleportation.

During the past year, Professor Paola Cappellaro's Quantum Engineering Group has devised several strategies to improve quantum sensors associated with spin defects in diamond. Nanoscale magnetic resonance imaging enabled by quantum sensors is a promising path toward the goal of determining the structure of single bio-molecules at room temperature.

The first technique developed by the group, labeled "quantum interpolation," can improve the frequency resolution of these quantum sensors far beyond limitations set by the experimental controlling apparatus. The method relies on quantum interference to achieve high-fidelity interpolation of the quantum dynamics between hardware-allowed time samplings, thus allowing high-resolution sensing. The group demonstrated resolution gains of more than two orders of magnitude and discussed applications of their work to high-resolution nanoscale magnetic resonance imaging.

The second technique addresses the problem of sensing slowly varying magnetic fields, a task particularly relevant to many real-world scenarios. With quantum spin probes in diamond, the standard technique for measuring DC magnetic fields is the Ramsey technique, which is limited by the fast dephasing time due to environmental noise. The group devised a nuclear spin-mediated technique that allows much longer interrogation times. The method relies on frequency up-conversion of the DC field by the hyperfine coupled ancilla, allowing quantum lock-in detection. In conjunction with Ramsey detection, it also provides a valuable tool for vector DC magnetometry at the nanoscale.

Finally, the group used feedback to achieve a nuclear spin gyroscope with hour-long stability. Specifically, they used information extracted from measuring the electronic spin state of defects in diamond to correct for environmental fluctuations affecting nuclear spin. Thanks to this intrinsic feedback scheme, they were able to extend the stability of their gyroscope to a few hours, much longer than commercial devices.

Professor Isaac Chuang's group studies theoretical and experimental quantum information science and seeks to harness the laws of quantum physics to solve difficult problems faster than is possible with conventional computers. The group recently invented a new quantum algorithm for "fixed-point quantum search" that uncovers solutions to unstructured search problems in a square root of the time required by a comparable classical algorithm, regardless of the number of marked solutions. This algorithm circumvents the no-go theorem previously thought to prohibit such a speedup. Professor Chuang's group has also discovered a method to enhance imaging using quantum coherence, resolving the position of objects at a Heisenberg limited speed. Both discoveries utilize ideas from discrete time signal processing and are shaping the creation of a new field of quantum signal processing.

Professor Terry Orlando, Research Scientist Simon Gustavsson, and Professor William D. Oliver direct a multi-university, multidisciplinary research effort focused on using superconducting circuits for quantum computation. Their research uses advanced techniques of quantum control and noise spectroscopy to characterize and improve the performance of superconducting qubits, and the group's work is performed in close collaboration with Professor Oliver's team at Lincoln Laboratory. The focus over the past year was on projects related to improving the readout of superconducting qubits.

The state of a superconducting qubit is typically inferred by exposing the qubit to microwave radiation and measuring the properties of the transmitted/reflected signals. Detection of the minuscule microwave signals used for qubit readout requires an amplifier capable of faithfully amplifying the small signal while adding a minimal amount of extra noise. During the year, the group studied the properties of novel superconducting traveling-wave parametric amplifiers, which contain chains of thousands of superconducting junctions acting as nonlinear amplifying elements. Using these devices, the group demonstrated single-shot qubit readout with a fidelity above 96%. This work was a collaboration among MIT, Lincoln Laboratory, and the University of California, Berkeley.

In a separate project, the group investigated using squeezed light as a method to improve the fidelity of the qubit readout. Quantum mechanics allow for minimizing (squeezing) fluctuations in one quadrature of the radiation field at the expense of increased fluctuations in the other quadrature. Using two-mode squeezed light and aligning the squeezed quadratures with those relevant for detecting the qubit state, the group showed that the squeezed light can substantially improve qubit readout efficiency when scaling to larger systems involving many qubits and many readout photons. This work was a collaboration between the MIT group and researchers at McGill University and the Université de Sherbrooke.

In a collaboration with Professor Jonas Bylander and his group at Chalmers University of Technology in Gothenburg, Sweden, the MIT group demonstrated a new readout technique based on coupling the qubit to a frequency-tunable and nonlinear superconducting resonator known as the Josephson parametric oscillator. By modulating the frequency of the device at twice its resonant frequency, it was shown that information about the qubit state can be mapped onto the strong parametric response of the resonator. The technique yielded enough signal-to-noise ratio to perform a single-shot readout of a superconducting qubit, a necessity in many quantum information protocols.

Both in the lab of Professor Orlando, Dr. Gustavsson, and Professor Oliver and elsewhere around the world, there has been tremendous improvement in coherence times and the achievable gate fidelities of superconducting qubits. As quantum information science moves from a laboratory curiosity to the threshold of technical reality, with multiple corporations investing in these and supporting related technologies, there is an opportunity for university growth in a new discipline: quantum engineering.

Professor Jeffrey Shapiro and Senior Research Scientist Franco N.C. Wong have been working on theory and experiments related to reaching ultimate quantum limits in communication and imaging at optical frequencies, where quantum noise is often dominant and conventional techniques are known not to reach ultimate performance limits. This year the group had a major achievement in quantum communication with the development of a novel method for securely distributing encryption keys. By sending many photons per bit spread over a large number of optical spectral modes, the new protocol, called floodlight quantum key distribution, overcomes channel loss to potentially achieve a gigabit per second key generation rate that is suitable for practical encryption of large files. At the same time, the injection of coincident photon pairs and the use of channel monitoring of their coincidence level, together with the no-cloning theorem of quantum physics, enable the protocol to be secure against both passive and active eavesdropping. The theory of the new protocol may lead to its practical use in quantum-secured communication.

The Shapiro-Wong group scored a second major achievement this year with the demonstration of a new photon-efficient imaging technique using a single-photon camera. The technique uses an array of single-photon detectors with nanosecond timing capability for imaging a scene at low-light-level conditions. A new algorithm was developed for reconstructing the scene's 3D structure and reflectivity accurately by exploiting both the transverse smoothness and longitudinal sparsity of natural scenes. By incorporating the single-photon camera's functional characteristics and imperfections, the new technique achieves high photon efficiency in a relatively short acquisition time. The new imaging method promises significant speed-up in practical laser-radar acquisition times.

Personnel

In July 2016 Polina Anikeeva was promoted to associate professor, and Paola Cappellaro was promoted to associate professor with tenure.

In September 2015, Professor Rahul Sarpeshkar left MIT to join Dartmouth College as the lead faculty member in the Neukom cluster, which will explore the computational and engineering principles of intelligence.

Marybeth Corcoran (financial coordinator), Noah Lillian Drori (strategic initiatives program manager), Todd Numan (environment, health, and safety coordinator), Paul Palei (information technology desktop consultant), and Sampson Wilcox (web and media designer) joined RLE headquarters this year. Susan Parker and Melissa Sheehan were promoted to senior fiscal officers, Cathy Borgeson and Joseph Foley were promoted to fiscal officers, and Stephanie Muto was promoted to senior financial assistant. During the year, Noah Drori left RLE headquarters to join Advanced Functional Fabrics of America. Krista Van Guilder also left MIT to pursue other employment opportunities.

The RLE community lost two respected and beloved former members this year:

- Abraham (Abe) Bers ScD ’59, professor emeritus of electrical engineering, died in September at the age of 85. Bers, who was recognized on campus for his trademark neatly squared bowties, was known both for his accomplishments in the field of plasma physics and for his contributions as a gifted educator.
- John Wyatt ’68, who served as a professor of electrical engineering for 36 years, passed away in February; he was 69. Wyatt was a devoted researcher who spent decades developing retinal implants to restore sight to people affected by age-related macular degeneration and retinitis pigmentosa, the two leading causes of blindness worldwide. An expert in circuits, his work focused on developing a chip that could be implanted in the retina to transmit visual information to the optic nerve.

Faculty Honors and Awards

Professor Elfar Adalsteinsson was inducted into the College of Fellows of the American Institute for Medical and Biological Engineering Elite on April 4, 2016. He was recognized for his leadership in the development of multiple fast imaging and parallel transmission methods and bringing state-of-the-art signal processing and optimization strategies to clinical MRI.

Professor Polina Anikeeva received the Class of 1942 Career Development Assistant Professorship, was named one of *MIT Technology Review*’s 35 Innovators Under 35, and won the Junior Bose Award for Excellence in Teaching.

Professor Karl Berggren became a fellow of IEEE and the American Association for the Advancement of Science and received the Optical Society of America (OSA) Paul F. Forman Engineering Excellence Award.

Professor Paola Cappellaro was named associate editor of the journal *Quantum Information Processing* in 2016.

Professor Luca Daniel received the Ruth and Joel Spira Award for Excellence in Teaching from the MIT School of Engineering in May 2016. During the past year, two of his students won MTL Doctoral Dissertation Seminar Awards. Professor Daniel also received the Best Paper Award at the IEEE Design Automation Conference in March 2016.

Professor Mildred Dresselhaus was selected by Thomson Reuters for inclusion in its Highly Cited Researchers list, which recognizes the world’s most influential researchers. Professor Dresselhaus also received four honorary degrees over the past year, from ETH Zurich (the counterpart of MIT in Europe), Tohoku University in Japan, Brandeis University in the Boston area, and Oxford University in the United Kingdom.

Professor Yoel Fink, former director of RLE and a leader in cutting-edge research on multi-material and multi-functional fibers, won the 2016 Collier Medal along with colleague Neri Oxman for providing incredible support to one of Professor Oxman's students diagnosed with a brain tumor. They were nominated by the student/patient for helping attain the best surgeon using the latest technology with genome sequencing and for remaining by his side throughout the entire treatment and follow-up care.

Professor James Fujimoto received the Fredrick Ives Medal/Jarus W. Quinn Prize from the Optical Society of America in October 2015 "for pioneering the field of optical coherence tomography (OCT) and for leading the field to widespread medical application and major commercial impact." The Ives Medal recognizes overall distinction in optics and is the society's highest award. Also, Professor Fujimoto co-edited (with Professor David Huang, who co-invented OCT during his doctoral program at MIT) a special issue of *Investigative Ophthalmology and Visual Science* commemorating the 25th anniversary of the invention of OCT. Approximately 80 papers from leading international groups in ophthalmology were published in the open access special issue, including an invited paper by Fujimoto and Eric Swanson on the development, commercialization, and impact of OCT.

Professor Jeffrey Grossman was named a 2016 MacVicar Faculty Fellow for his ability to think deeply and strategically about education and to transfer his enthusiasm to his students.

Professor Jongyoon Han was awarded the Frank Quick Faculty Research Innovation Fellowship in November 2015.

Thomas Heldt (currently the Hermann L.F. von Helmholtz Career Development Professor) was named the W.M. Keck Career Development Assistant Professor. He will assume the new chair effective July 1, 2016. Also, Professor Heldt received the Louis D. Smullin ('39) Excellence in Teaching Award in May 2016.

Jeehwan Kim won the 2015 LAM Research Foundation Award in December 2015 and the 2016 IBM Faculty Award in June 2016.

Professor Jing Kong was recognized on the Thomson Reuters Highly Cited Researchers list as one of the world's most influential researchers.

Professor Tim Lu was the recipient of the 2015 *ACS Synthetic Biology* Young Investigator Award, which recognizes the contributions of a scientist who has had a major early-career impact on the field of synthetic biology. Professor Lu also received the 2015 *Biochemical Engineering Journal* Young Investigator Award. This award recognizes outstanding research and practice contributed to the field of biochemical engineering by a young community member.

Professor Muriel Médard received a James Evans Avant Garde Award from the IEEE Vehicular Technology Society.

Professor David Perreault received the IEEE R. David Middlebrook Achievement Award for his paper "Miniaturized Low-Voltage Power Converters with Fast Dynamic Response," which was published in the *IEEE Journal of Emerging and Selected Topics in Power Electronics*.

Professor Katharina Ribbeck won the 2015–2016 Harold E. Edgerton Faculty Achievement Award.

Thomson Reuters named Professor Yang Shao-Horn to its Highly Cited Researchers list as one of the world's most influential researchers.

In a special session organized by her colleagues, Professor Stefanie Shattuck-Hufnagel was recognized for her work in connection with the 2016 Speech Prosody meeting in Boston in June 2016. One of her students received a Best Student Paper Award at the International Congress of Phonetic Sciences in Glasgow.

Professor Vivienne Sze received the Young Investigator Research Program Award from the Air Force Office of Scientific Research for her work in energy-efficient high-performance computer vision systems in March 2016.

Professor Martin Zwierlein was recognized on the Thomson Reuters Highly Cited Researchers list as one of the world's most influential researchers.

Staff Awards

The following RLE community members won 2016 Infinite Mile Awards from the Office of the Vice President for Research: Donna Gale, administrative assistant for LEEDS; Elizabeth Hoy, administrative assistant for Martha Gray and the MIT Madrid program; Mark Mondol, assistant director of the Nanostructures Laboratory; and James Daley, research specialist for the Nanostructures Laboratory. Mondol and Daley maintain a fully operational suite of state-of-the-art nanofabrication equipment.

Student Awards

The 2016 Helen Carr Peake Research Prizes have not yet been awarded. The prize committee will meet in late September to discuss the six nominations for this annual RLE student award.

The 2015–2016 Claude E. Shannon Research Assistantships were awarded to Christina Lee and Quntao Zhuang, doctoral students in the Department of Electrical Engineering and Computer Science. These students were recognized for their outstanding research projects in communications. Lee's research is supervised by Professor Devavrat Shah in the Operations Research Center in the Laboratory for Information and Decision Systems. She received the award based on her research in the emerging area of social networks and data processing, particularly in performing inference using behavioral models and the challenge of computing at this scale. Zhuang's research is supervised by Professor Jeffrey Shapiro in the Optical and Quantum Communications Group in the Research Laboratory of Electronics. His research focuses on quantum information and communication, particularly on emerging problem areas in quantum key distribution.

Affirmative Action and Outreach Activities

RLE will continue working to increase the number of women and minorities in career positions in the laboratory. Specific measures include maintaining our high standards for recruitment procedures, among them sending job postings to organizations for professionals of color, working closely with the RLE faculty/staff supervisor at the beginning of each search to identify ways of recruiting minority and female candidates, and being committed to finding new techniques to identify women and minority candidates more effectively. During the past year, RLE appointed one woman to an exempt-level staff position in headquarters.

RLE has continued its work in nurturing future generations of engineers and scientists. Again this year, the Center for Ultracold Atoms conducted a program to stimulate the careers of undergraduate physics majors who are thinking of becoming teachers in the physical sciences at the pre-college level. The program, Teaching Opportunities in the Physical Sciences (TOPS), involved eight undergraduate physics majors, mostly juniors, who were recruited from colleges and universities across the nation. The central TOPS activity was the experience of actual teaching. Two teams of students worked under the direction of a master teacher to prepare and teach students at the middle school and high school levels. Middle and high school students were recruited largely from local schools, with some traveling from other states to take part. This was the 14th year in which the center ran the program.

We are extremely grateful for the profound dedication of the RLE principal investigators, their continued focus on innovative and inspirational research, and their passionate commitment to the lab, to MIT, and to the world of science.

Marc A. Baldo
Interim Director
Professor of Electrical Engineering and Computer Science