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 groundbreaking 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 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 and 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 conduct research directly involving 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 establishment of best practices at MIT. This role for the lab is being fulfilled on several important fronts. RLE has initiated a number of programs addressing important lab objectives that, 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, and the Translational Fellows Program (TFP), an initiative accelerating the rate of technology translation and creating jobs for postdocs.

With a research volume of $53 million in fiscal year 2015, the lab continued to be one of the Institute's leading research organizations. From 2014 to 2015, there was a healthy 9% increase in research volume. RLE manages more than 200 active research projects and services for over 70 principal investigators. In fiscal year 2015, nearly 300 graduate students (approximately 260 of whom are research assistants) and 105 undergraduates worked in various labs.

Since 2011, RLE has been endowed primarily by royalties from high-definition 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, 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 while strategically deploying 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. RLE would like to be viewed as a place where novel approaches aimed at increasing productivity and efficiency are envisioned, developed, and tested for MIT at large. 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 (PLAN), as well as certification for RLE administrative assistants through the Leading Excellence in Administration Program.

Figure 1. RLE's seven major research themes.

Service Survey

To provide the highest level of service and look for new opportunities to help support our faculty, we assess our services every other year 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. The next RLE service survey is scheduled for 2016.

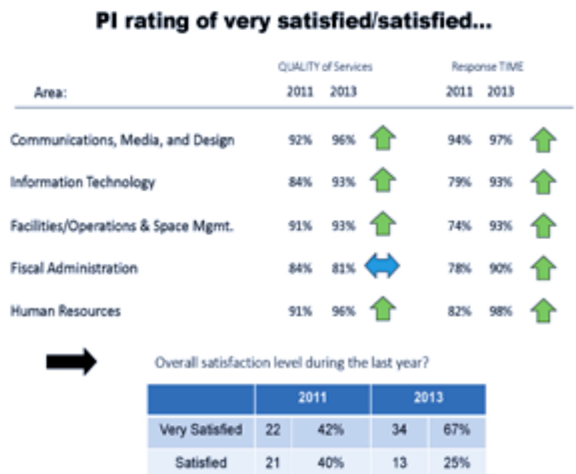

Figure 2. RLE Service Survey; an overview of satisfaction levels for 2011 and 2013

Goals

Each year RLE focuses on a select group of key initiatives designed with specific objectives in mind. Our 2015 goals centered around five strategic areas: building community, stimulating discovery, developing resources, applying impact, and pursuing quality and efficiency. We continue to take active steps and design targeted programs to accomplish these goals.

Figure 3. RLE goals for 2015

Initiatives and Events

RLE Immersion

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.

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. RLE wondered whether there were additional measures that could accelerate the translation of research-to-impact. Our hypothesis is that the rate of conversion of ideas derived from basic research to products can be significantly increased through deliberate actions.

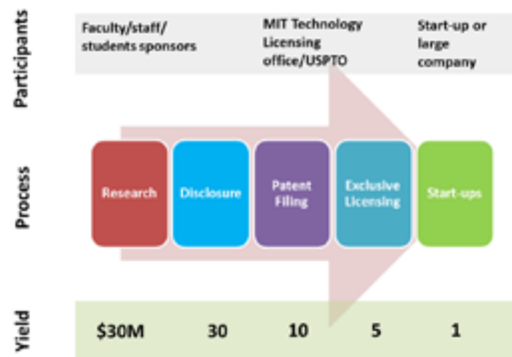

Figure 4. MIT annual commercialization snapshot from basic research funding (dollars) to technology disclosures, patent filings, exclusive licenses, and startups (normalized per startup).

During 2014–2015, RLE piloted a new 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 of 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 and beyond 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, importantly, 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, the Department of Materials Science and Engineering, and the Department of Physics, the 2014–2015 pilot year expanded to 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 more. 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 upcoming year will be critical in refining the scalability of the 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. We are moving forward with connections made and spending time adapting and evolving our process to best target fruitful collaborations for our PIs.

Low Cost Renovation Study

RLE has continued investigating the cost drivers behind on-campus renovations. The Low Cost Renovation Study is based on a collaborative approach, in cooperation with the MIT Department of Facilities, to gather data and jointly assess 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. This year, a renovation of Professor Martin Zwierlein's space for studying ultra-cold atoms was completed. The Department of Facilities has commissioned RLE to expand the study to include two more external projects: the renovation of the Kavli Institute 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.

Preliminary findings 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. For example:

- The lab leverages a long-term relationship and high level of trust with the PI.
- The PI and the lab work on risk management.
- The lab works with the PI to optimize value and cost.
- The lab works with MIT's Department of Facilities to align practices with needs.
- Bidding costs and project execution are tightly managed.
- There is constant coordination among the PI, the engineer, the lab, and Facilities.
- Trust is established between the DLC and Facilities through cooperation.
- The DLC accomplishes renovations while complying with city codes, safety programs, union agreements, and MIT insurance and contracting requirements.

Our preliminary recommendations and conclusions are as follows:

We recommend that the study be expanded to other renovation-enabled DLCs to continue to establish costs, quality, and a compliance model.

We support a tenant-based renovation approach; tenants can choose to either manage the renovation themselves or have Facilities do so.

We recommend that building infrastructure costs be separated from the renovation.

We recommend investing in a DLC guide to internal renovations for the purpose of clarifying MIT building practices, necessary permits, and internal signatures and approvals.

> We recommend that a common database be established for best building practices, project costs, and so forth, and that it be shared across the Institute to increase transparency and enhance organizational learning and improvement.
>
> We believe that it is critical to establish building comparisons with industry and academia to help benchmark costs.

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 the preconstruction, 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 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, tools, and techniques for applying best practices in leadership and management. In March 2015, 25 postdocs from a wide variety of RLE research groups attended a project management workshop. Leslie Weiner Alger, a former group leader at MIT Lincoln Laboratory and now an executive coach, delivered the workshop, which was geared toward helping participants become more effective project team members and project leaders. RLE postdocs learned about the life cycle of a project, including initiation, planning, execution, and closeout, with a particular emphasis on project planning. There was also a section on effective delegation and another on risk management, particularly as it applies to research projects.

Leading Excellence in Administration Program

RLE continued the Leading Excellence in Administration Program for RLE administrative assistants. This training program, consisting of monthly workshops, was created to support and enhance the administrative, human resources, fiscal, and computer skills of RLE's administrative assistants. The program began in summer 2014 and ended in early June 2015. Workshop 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 included financial review and control procedures, audits and compliance, performance reviews, RLE's digital and HR processes, event planning, SAP reporting and processes, fabrication account management, Concur travel procedures, and effective writing skills. Nine assistants completed a minimum of nine of the 12 workshops to receive this year's certification: Janice Balzer, Dimonika Bray, Susan Davco, Shayne Fernandes, Dorothy Fleischer, Paula Sack, Read Schusky, Laura von Bosau, and Arlene Wint.

Laboratories and Research Highlights

The 2014–2015 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 including 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.

In 2015 the Ketterle group 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 in 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 and provide new understandings of important physical phenomena. This year, Professor Vuletic's group reported two breakthrough experiments. In an article published in *Nature*, the group reported the largest state with quantum mechanical correlations (entanglement) ever achieved, with 3,000 atoms included in the entanglement. This type of state can be used to improve atomic clocks and other precision measurements with atoms.

Another paper that received significant media attention after its publication in *Science* described a simulation of nanoscopic friction using a chain of laser-cooled ions. Professor Vuletic and his group showed that with a slight rearrangement of the atoms, the system can make a transition from a high-friction to a nearly frictionless regime. The paper demonstrated experimentally that friction can be reduced by a large factor through making the atomic lattices of the sliding object and of the substrate incommensurate. This had previously been known theoretically for infinitely long chains; what came as a surprise to even the specialists is that a hundredfold suppression of friction can be observed for an object as small as six atoms. This potential to reduce or tune friction may be important for nanomachines that, as a result of 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 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 realization of a quantum gas microscope for fermionic atoms and the first creation of an ultra-cold gas of chemically stable fermionic 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. Physics takes place at much slower time scales and at much larger distances than in condensed matter systems, so one is able to follow the evolution of a quantum system in real time—of course, within the constraints posed by quantum mechanics. Before the advent of the Fermi gas microscope, only data on the average distribution of atoms could be collected. Now the position of every atom can be imaged, and in principle each single atom can be manipulated at will. Such detection and control at the single-particle level do not exist for electrons. Importantly, the imaging scheme itself does not significantly heat the gas but leaves each atom in the quantum-mechanical ground state of its lattice site with high fidelity. This might enable Maxwell's demon–type experiments wherein each atom can be detected and repositioned at will. This coherent control might enable quantum computations with fermions.

In view of the immense success of ultra-cold atomic gases, researchers have long desired to extend cooling techniques to more complex molecules. Ultra-cold molecules were proposed as ideal carriers for quantum information, for precision tests of fundamental laws of nature, and for quantum chemistry and as quantum simulators for condensed matter systems. However, the same complexity that makes them interesting for applications makes them difficult to cool. Molecules can rotate and vibrate, and these additional degrees of freedom need to be controlled. Also, molecules should not undergo chemical reactions, as they would then not form a stable gas one could work with. The Zwierlein group succeeded in creating the first ultra-cold Fermi gas of chemically stable molecules. They started with a mixture of two atomic gases, sodium and potassium, and essentially "glued" the atoms together to form NaK (sodium potassium) molecules using so-called Feshbach resonance, named after MIT's late Herman Feshbach. These Feshbach molecules are more or less two atoms on a stick, with the typical distance between the two atoms quite large from a chemistry perspective, about two-hundredths of a human hair. To transfer the molecules into the absolute lowest state of vibration, the Zwierlein group used two laser beams whose frequency difference matched the energy difference between the Feshbach state and the lowest vibrational state of the molecule. In terms of temperature, this trick removed 7500 Kelvin worth of energy. The team was left with a gas of ultra-cold molecules that were in their lowest state of vibration, rotation, and even nuclear spin alignment. These molecular gases promise to yield new states of matter thanks to their unusual dipolar (magnet-like) interactions.

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 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 (published in *Nature Materials*) is his group's demonstration, together with Vladimir Bulović in EECS and Moungi Bawendi and Troy Van Voorhis in the MIT Department of Chemistry, of energy transfer from organic molecules to semiconductor nanocrystals. This work is expected to provide a bridge between conventional semiconductors and the important nonlinear properties of organic materials, including exciton fission and exciton fusion.

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: a small-scale micro-grid analog emulator is now operating, and an emulator of a solar photovoltaic source is now part of the system. The capacity of the system is being enhanced with a second engine-generator emulator so that inter-area swings and multiple micro-grids can be investigated. In addition, enhanced instrumentation has been designed and built for the system, which will soon include phase measurement units allowing sophisticated experiments to be carried out. 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. In particular, the team is collaborating with Dr. Jimmy Peng on advanced system control and monitoring (using phase measurement units) and with Dr. Mohamed el Moursi on micro-grid controls.

Kirtley's group is about to embark on a related project, sponsored by a manufacturer of power line monitoring equipment, to simulate the dynamics of micro-grids for the purpose of improving control and stability. It is anticipated that the analog micro-grid emulator will be used to verify the simulations.

Working with MIT Professor Steven Leeb, Dr. Kirtley and a PhD student are investigating large motor drives for ship propulsion. A conceptual drive system has now been demonstrated. By using a doubly fed induction motor drive and a separate DC source, a system can have very stealthy operations at low speed and a power electronics package that has a rating no more than one third of drive system power requirements. The ability to achieve a near-humpless transition between low-speed stealth and high-speed doubly fed machine modes of operation has also been demonstrated. This year, improvements have been made to the drive hardware to reduce component counts and further smooth the transition.

The team's work on compact permanent magnet motors for mobile robots, in association with Professor Jeffrey Lang and a PhD student, is nearing conclusion. An experimental motor has been designed and built and is now being tested. That work has been extended to other mobile applications such as bicycle wheels. The group is now starting to conduct analyses with the anticipation of designing a flux-switching permanent magnet motor for an electric motorcycle.

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- and nanoscale electromechanical actuators and sensors, and distributed electromechanical structures.

Working with Professors Kirtley and Lang, graduate student Matthew Angle has developed a motor for mobile robot and traction applications that offers a considerable improvement in torque and power density as well as efficiency. Use of the motor has been demonstrated in the MIT Cheetah Project directed by Professor Sangbae Kim, and it has been shown to improve the performance of the project's quadruped running robot. During the past year, the team's design optimization was extended beyond the consideration of traditional three-phase motors. This resulted in a motor with a high phase count that offers yet better performance, including a significant increase in peak torque together with a simultaneous reduction in mass.

A team of graduate students and postdocs under the supervision of Professor Lang and Professors Vladimir Bulović and Timothy Swager have demonstrated a nanoelectromechanical 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 106. The importance of the molecular monolayer is that it prevents contact stiction, thereby eliminating a major impediment to using nanoelectromechanical relays for low-voltage digital logic and radio frequency (RF) switching. Current work focuses on reducing actuation voltage and energy, improving fabrication yield, and simultaneously increasing the ratio of on-state to off-state conduction.

Graduate students Rakesh Kumar and Tyler Hammer, working with Professor David Trumper and Professor Lang, have initiated a project to design, build, and demonstrate electroquasistatic (EQS) sensors for the 3D imagining of integrated circuits. Arrays of EQS sensors can be used to detect both surface and buried features and defects, allowing for the nondestructive evaluation and quality control maintenance of integrated circuits. EQS sensors differ from similar imagers such as atomic force microscopes and scanning capacitance microscopes in that they can image depth-wise into an object instead of just imaging its surface, allowing them to distinguish buried conductors/insulators and doped regions. The proposed system promises to offer very high measurement bandwidth, enabling rapid measurement of large areas with high resolution, which is critical to the time-efficient scanning of complex semiconductor wafers.

Professor Lang and graduate student Matthew D'Asaro have developed a low-cost 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. Work is now under way to improve the selectivity and sensitivity of the skin and to fabricate it through a wide-area printing process.

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 their work on developing noncontact magnetic and electric sensors for nonintrusive power monitoring. The new approaches pioneered this year permit installation of high-speed monitoring equipment at any site that uses electricity without the need for a skilled installer or electrical shutdown. Access and expense with regard to installing sensors are key factors limiting widespread data monitoring and analysis of energy consumption and critical load diagnostics.

- Developed NILMmanager, an “energy apps” cloud computing tool that enables the use of a nonintrusive load monitor as an energy box that can be controlled and monitored from anywhere on the Internet. Preliminary installations of this software have been made on the US Army Base Camp Integration Laboratory at Ft. Devens in Massachusetts and on board US Navy and US Coast Guard ships.
- Continued the development of a new approach for processing energy from solar arrays that uses no external inductors or capacitors. The diffusion capacitance of the solar cells in the array serves as the energy storage mechanism for the power converters that perform maximum power point tracking. This year, a combined approach using diffusion capacitance and differential power processing was demonstrated to provide the highest levels of efficiency. A patent filing was completed for this work.
- Created a new power electronic transfer switch for ship propulsors that requires power electronics rated at only one third or less of full machine shaft power while providing full speed control. This new transfer switch minimizes the need for semiconductors on the stator side of the machine and offers exceptional control for high-bandwidth propulsion applications.
- Generated and demonstrated new techniques for using power system monitoring for vibration detection. The group is using these techniques to improve the “underway” acoustic signature of United States Navy warships. Over the past year, this work was conducted on board the USS Champion in San Diego.

Professor David Perreault’s research focuses on advancing power electronics technology and on the use of power electronics to benefit important 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, LED lighting, and grid-interface power supplies. One important result has been the development of improved models for planar power magnetic components. This research, which has led to conference and journal papers and the development of a software tool, enables rapid modeling of the inductance and loss of planar magnetic components, allowing faster and improved optimization of such components. Professor Perreault’s work has been utilized in the development of a new highly integrated power supply for telecom systems. This design involves a hybrid magnetic/switched capacitor approach enabling very wide input voltage range operations while preserving high efficiency and power density. The first-generation prototype has threefold higher power density than any commercial design known, due to both the adopted architecture and the optimization of the transformer. This work has led to a conference publication and patent filing. Work is ongoing to adapt this hybrid magnetic/switched capacitor approach to grid-interface power supplies, where it is expected to provide excellent performance.

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 five major projects:

- The group has been studying the design of high-linearity iron core actuators for precision motion control systems, including magnetically levitated stages for semiconductor manufacturing.
- In a collaboration with Dave Barrett of Olin College, the group has been investigating a new type of actuation system for autonomous marine robotic locomotion.
- In a collaboration with Boston Children's Hospital, the team has been studying magnetic designs for the treatment and correction of esophageal atresia, a condition in newborns in which the esophagus is not connected to the stomach. This approach has the potential to eliminate the need for invasive surgical procedures, which are required in the current treatments.
- In work with Professors Jeff Lang and Markus Zahn, Professor Trumper is investigating an electromagnetic nanoimager that uses electric and magnetic fields to image surfaces with nanometer-scale resolution.
- Professor Trumper has embarked on a new collaboration with Professor Linda Griffith in which they are exploring microphysiological systems for the in vitro study of human organ tissues such as lung, gut, endometrium, and liver cells.

Information Science and Systems

Research in this area spans a complete range of activities over 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 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 security 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 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 Labs as partners. Through collaborative efforts with Bell Laboratories and the University of Texas at Dallas, the MIT team invented a new algorithm to dynamically and rapidly 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.

With respect to reliable network delivery of critical messages, a new routing and transport algorithm was created to ensure timely delivery of critical messages such as disaster warnings. The technique should be ready for patent filing in the fall of 2015.

Professor Chan is currently chairing the Defense Science Board Task Force on Military Communications and Networks and a Department of Homeland Security blue ribbon panel to examine the agency’s cybersecurity system. A yearlong Defense Advanced Research Projects Agency study to create new network research directions is under way, and a comprehensive report will be issued in fall 2015. Professor Chan is also participating in a congressionally directed National Research Council study on national security space defense and protection.

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 biological sensors, multimedia processing, and energy conversion. Highlights from the group this year are in the areas of biosensors, video decoding, and wireless communication.

In collaboration with Professor Tim Lu, the team has completed the design and simulation of a system for the detection of gastrointestinal (GI) diseases based on synthetically engineered bacteria and a CMOS (complementary metal-oxide-semiconductor) microelectronics platform. In this platform, microbes are genetically engineered with reporter genes sensitive to biomarkers for diseases of the GI tract. The microbes signal the circuitry via luminescence, which then triggers wireless reporting to the user’s smartphone or tablet. This project won the 2014–2015 Qualcomm Innovation Fellowship competition. Preliminary work on the electronics for this system led to a new ultra-low-energy timer/oscillator circuit that consumed 4.2pW for 18 Hz of oscillation.

In collaboration with Professor Vivienne Sze, the team developed energy-saving techniques for video decompression in hardware. Video decompression standards such as H.264/AVC (advanced video coding) and HEVC (high-efficiency video coding) require storing up to 16 previous frames in memory. The group developed ways to efficiently store these frames in Embedded DRAM (EDRAM). EDRAM is integrated with processing logic on the same die, which provides significantly higher bandwidth at a lower energy per access level than conventional off-chip DRAM. While previous work has targeted energy reduction for video decoders with off-chip DRAM, the Chandrakasan team targets idle-power consumption of EDRAM as it accounts for a significant portion of the total power in the design. The use of compression allows them to power down unused blocks and achieve fine-grained data-dependent power scaling.

In a collaboration with Professor Muriel Médard, the team established efficient protocols for wireless sensor networks (WSNs), achieving the required communications reliability while maintaining low power operation even in harsh environments. In addition, they recently developed AdaptCast, an integrated representation-to-transmission physical layer architecture for WSNs. AdaptCast leverages the sparsity inherent in the majority of physical signals (e.g., biomedical signals, natural images) encountered in WSNs in order to parsimoniously represent them and increase their robustness against channel errors. Apart from point-to-point links, AdaptCast enables efficient multicasting to a set of nodes, offering rates commensurate to their individual channel quality.

Professor Luca Daniel leads the Computational Prototyping Group with Professor Jacob White. Recently, stochastic spectral methods have received attention and recognition in the electronic design automation community for their performance in statistical characterization of electronic circuits. During the last year, the Daniel group has focused on developing "hierarchical" stochastic spectral methods. In stochastic spectral methods, one needs to determine a set of orthonormal polynomials and a proper numerical quadrature rule. Obtaining such information requires knowing the density function of the random input a priori. However, individual system components are often described by surrogate models rather than by density functions. In order to apply stochastic spectral methods in hierarchical uncertainty quantification, the group first proposed constructing physically consistent closed-form density functions in two monotone interpolation schemes. Then, by exploiting the special forms of the obtained density functions, they determined the generalized polynomial-chaos basis functions and the Gauss quadrature rules that are required by a stochastic spectral simulator. The effectiveness of their proposed algorithm was verified in several practical circuit examples.

In a coupled parallel transmit array for magnetic resonance imaging (MRI) scanners, the power delivered to each channel antenna is partially distributed to other antennas because of coupling. This power is dissipated in the circulators, resulting in a significant reduction in the power efficiency of the overall system. Most existing decoupling methods focus on nearest neighboring channels. Capacitive ladder networks, which aim at also decoupling distant neighbors, are rarely used because they are highly sensitive to specific operating conditions. The Daniel group has proposed instead an automated approach to designing robust decoupling matrices interfaced between the RF amplifiers and the coils. The decoupling condition is that the impedance matrix seen by the power amplifiers is a diagonal matrix with 50 ohms at the diagonal. Intuitively, a dense full-rank matrix can be converted to a diagonal matrix through eigendecomposition. In this work, the group diagonalized the impedance matrix of the coupled coils (or antennas) by multiplication with its eigenvectors. They accomplished this multiplication via Givens rotations implemented using only passive RF components such as hybrid couplers and lumped reactive elements. The group has fabricated an actual decoupler designed through their algorithm, and the results show near-ideal decoupling. The Daniel group has filed a patent with Siemens on this new technology, and they expect it to be used in both research and industrial settings.

This past year Professor White's research group has focused on fast-volume integral equation methods for problems in magnetic resonance imaging, nanoscale power transfer, and induction heating, as well as exploring problems in large-scale power systems.

This summer, the group released MARIE (MAgnetic Resonance imaging analysis with Integral Equations), their software for computing detailed 3D electromagnetic field patterns in realistic human body models. The techniques in MARIE reduce field computation time from days to minutes and down to seconds for repeated evaluations with modified coil geometries and excitations. MARIE is based on the group's recently developed fast-volume integral equation methods and sparse-projection-based reduction schemes; a recent presentation on the software received a Summa Cum Laude award at the meeting of the International Society for Magnetic Resonance in Medicine.

The team has already demonstrated that the volume integral equation techniques in MARIE can be adapted to computing nanoscale power transfer, and they are currently investigating how to use the methods for electrical property extraction, ultrasound imaging, and microfluidics-based desalination.

The research of Professor Mildred Dresselhaus and her group focuses on using nanostructures to change and control the properties of materials relative to their bulk counterparts. Special emphasis in the past year has been given to focusing on new layered materials beyond graphene involving few-layered transition metal dichalcogenides and phosphorene, which the group has studied in the past in their bulk forms. Collaborative research programs with Jing Kong in EECS and Gang Chen in the Department of Mechanical Engineering have continued, as well as collaborations with researchers in North and South America, Europe, and Asia providing learning opportunities for students, postdocs, and faculty on the MIT campus.

Professor Jeffrey Grossman and his team focus on the computational and experimental design of novel materials for applications in water, energy conversion, and energy storage. Significant results from this year include a detailed understanding of pore formation in reduced graphene oxide for tailored separation membranes, the synthesis of a novel solid-state solar thermal fuel made from polymers, and the first-ever measurements of devices made from nanostructured coal that showed seven orders of magnitude tunability in electrical properties.

Professor Jae Lim's group is involved in the development of image and video processing methods. During the past year, their accomplishments include the development of new transforms and a new method to choose the best transform for different parts of images and videos. These results have the potential to be useful for the development of more efficient image and video compression systems.

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, Boston University, Northeastern University, Pennsylvania State University, Duke University, the Australian National University, KTH, Trinity College Dublin, the University of Waterloo, Steinwurf, CodeOn, and Alcatel-Lucent. The group's central theme is communications, 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 network coding techniques for non-multicast connections, new algorithms for network science in life sciences, algorithms for information-theoretic approaches to privacy and security, applications of network coding in power line communications, use of network coding to reduce transport delays, and probabilistic methods in forensics. The group's work was recognized with two Best Paper Awards at the IEEE (Institute of Electrical and Electronics Engineers) International Communications Conference and an IEEE International Symposium on Power Line Communications Best Paper Award.

Professor Vivienne Sze and the Energy-Efficient Multimedia Systems Group focus their research on development and implementation of energy-efficient and high-performance systems for various multimedia applications such as video coding/processing, imaging, and vision. 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: efficient compression algorithms that can be used for next-generation video coding and low-power architectures and algorithms for real-time object detection for embedded sensing applications (e.g., security, smartphones). Their work included a low-power, real-time high-definition object detection chip using HOG (histogram of oriented gradient) features that can detect multiple object sizes with only 45 mW of power. Additionally, they developed a new method for prediction using a rotated predictor that reduces error by more than 20%.

Professor Gregory Wornell's research focuses on algorithms and architectures for next-generation data compression, latency reduction in cloud infrastructure, and data security. In the area of compression technology, the Wornell group continued to develop a new compression architecture based on the concept of model-free encoding. In this architecture, the encoder is extremely simple and makes no use of the model for the content being compressed. Instead, only the decoder makes use of this model. However, no performance penalty is incurred. This new architecture has the potential to lead to a "perpetually upgradable" data compression standard, circumventing important problems with the current compression standards process. The group's recent results extend their architecture to arbitrary sources and to scenarios wherein there is a semantic model allowing for controlled distortion in source reconstruction.

In the area of algorithms and architectures for cloud infrastructure, the group obtained several key results. First, they showed how carefully designed redundant computation in cloud computing can be used to make efficient tradeoffs between latency and machine time in cloud computing. Second, the group has shown that redundant copies of content can be used to efficiently trade off latency and storage requirements in distributed storage infrastructure. Finally, they have developed new techniques for reducing delay in on-demand content streaming from such infrastructure.

With respect to data security, the Wornell group has two sets of results. The first are efficient and robust quantum secret key distribution techniques for optical channels. The second is a new result on the fundamental limits of communication subject to transmissions being undetectable to an adversary.

Professor Lizhong Zheng and his team have been working on applying information theory to a broad range of new problems in data analytics. Information theory has traditionally been applied to digital communication problems, and it has had great success in guiding the designs of communication and network systems. Current activities in machine learning and data mining require a new extension of the theoretical framework to ensure that the theory is applicable to the design and analysis of efficient algorithms, that it can process high dimensional data, and that it performs well in a dynamic environment.

Professor Zheng's recent work draws connections between information geometry and the feature extraction algorithms in data processing. With this approach, Professor Zheng's group has developed a new theory for information processing that allows a more systematic understanding of the nature of many existing algorithms and a fair assessment of their performance. They have also developed a new algorithm that can jointly process information across platforms, combine information, and automatically identify the most informative features in the data. The 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, and identification based on audio signals and images. Zheng believes that his group's approach will have an impact in defining a new architecture in the data processing industry.

Biomedical Science and Engineering

This theme encompasses thrusts in bio-inspired electronics and neural prostheses for hearing and sight, nano- and microtechnologies for understanding and manipulating biological processes at the cellular and molecular levels, imaging and computational modeling of disease and neuroanatomical 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 focus on medical imaging with MRI, with ongoing developments in estimation of brain oxygenation parameters via MRI; parallel transmission technology; image reconstruction methods for accelerated acquisitions through undersampling; and imaging of the unborn child and placenta. In an NIH-funded collaboration with Professor Ellen Grant of Boston Children's Hospital and Professor Larry Wald of Massachusetts General Hospital (MGH), Professor Adalsteinsson is addressing the relatively underserved space of fetal imaging, where traditional methods perform poorly due to involuntary subject motion and low tolerance for long scan times.

Professor Adalsteinsson is associate director of the Madrid-MIT M+Visión Consortium, which recruited a fourth class of fellows in the past year. The M+Visión Catalyst

Program continues to pay off in biomedical technology innovation, with fellows and their teams garnering awards and recognition for their efforts in areas ranging from entrepreneurship to academia.

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, in collaboration with Professor Yoel Fink's group at RLE, her lab has demonstrated fiber-based probes for simultaneous optical, electrical, and chemical communication with neurons in the brains of freely moving mice. These flexible polymer-based probes appeared to overcome the biocompatibility challenges of traditional neural interface devices. The fiber probes evoked negligible foreign-body response in the mouse brain over a three-month-long study. The Bioelectronics Group has also been pursuing minimally invasive and wireless approaches for neuromodulation. Leveraging hysteretic heat dissipation in magnetic nanoparticles, they have demonstrated robust and reversible neural stimulation with alternating magnetic fields in vitro and in deep brain structures of live mice. The group recently extended this technology to thermally triggered delivery of neuromodulatory compounds directly to neural membranes, allowing for cell-specific magneto-chemical neural activation. In addition to neuromodulation approaches, which may find future applications in the treatment of neurological and psychiatric disorders such as Parkinson's disease and major depression, the group has been developing tools to enhance and direct neural growth in the context of nerve repair following traumatic injury. Specifically, they have demonstrated that optical neural stimulation enhances nerve growth by over threefold. They have also used fiber-based fabrication approaches to produce a palette of neural scaffolds with diverse geometries, allowing demonstrations of the role of topographic features in nerve growth.

Professor Lou Braida and the Sensory Communication Group investigate 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 are focused 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 in 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. The team is developing a signal-processing technique that seeks to improve speech comprehension in environments with intermittent noise such as in a restaurant. Preliminary results indicate that this technique improves the performance of both normal and hearing-impaired listeners in fluctuating background noise.

The research in Professor Dennis Freeman's group explores the cochlear mechanisms that underlie the extraordinary properties of the sense of hearing, focusing primarily on sensitivity to low-amplitude sounds and acute frequency selectivity. The sharp frequency selectivity of auditory neurons, a hallmark of mammalian hearing, originates mechanically in the cochlea. Local resonance of the tectorial membrane (TM) is thought to play a key role. However, the presence of TM traveling waves demonstrates significant longitudinal coupling, which suggests an entirely different mechanism for controlling frequency selectivity by determining the spread of excitation across cochlear regions with different best frequencies. To understand spread of excitation and its origin, the group developed chemical manipulations that systematically and reversibly alter TM material properties. Using these chemical manipulations in conjunction with measurements of TM shear impedance and waves, the group showed that TM stiffness and viscosity both play significant but different roles in controlling the spread of excitation and tuning in the cochlea. Furthermore, they demonstrated that increasing the viscosity of the TM tends to decrease spread of excitation and thereby gives rise to sharper cochlear tuning, a result that is in striking opposition to prevailing theories of viscous loss mechanisms in the inner ear. The group's findings 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 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 Ludwig Maximilians University and Erlangen University in Germany. The group performs studies in clinical ophthalmology at the New England Eye Center, the UPMC Eye Center, and Oregon Health and Sciences University; gastroenterology and endoscopic studies at the Harvard Medical School and Boston VA Healthcare System; and pathology 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, leading causes of blindness.

The group also developed a next-generation prototype 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 published in the *Proceedings of the National Academy of Sciences*, they demonstrated that nonlinear microscopy could assess breast cancer pathology with sensitivity and specificity approaching that of standard histopathology.

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. Specifically, the M+Visión Catalyst Program is the "sandbox" through which she and her team are implementing and adapting a training program. The Catalyst Program has served to train both fellows and involved faculty. To date, 34 fellows have been recruited internationally, and they have formed teams that include over 100 collaborators from 88 research groups at 31 different institutions. Recruits spend the first four to six months of the fellowship defining and defending a portfolio of translational projects that address an unmet medical need for which there is high potential for impact. Through this process, 20 projects have been initiated since the program began. Fellows function, more or less, as PIs and work on teams that include other fellows, collaborators they recruit from institutions and hospitals, and catalysts and mentors from industry or relevant business communities in Madrid and Boston. Despite starting from scratch, many of these projects have already shown sufficient proof of concept to begin human studies or work on a project specification plan. The fellows and their projects have generated over 50 conference and journal publications, 25 invention disclosures, 15 patent applications, and seven grant awards totaling nearly $1 million. Highlights include the following.

- Team NeuroQWERTY: The team won the $100K Singapore Challenge and received a grant from the Michael J. Fox Foundation for their work on the creation of a new transparent technology to detect early signs of neurodegenerative disorders via finger interaction with electronic devices.
- Team Leuko: The team designed a project to enable people to better manage their own health through a technology that will allow non-evasive measurement of white blood cell counts, a first-line indicator of infection and risk of infection. The team received an NIH U54 grant for their work.
- Team Cell: The team developed a new approach to flow cytometry that will allow complex optical diagnostics such as lymphoma/leukemia subtyping without the need for multiple lasers and complex optics. Cytognos SL recently licensed this technology and is supporting further development. In addition, the team has been awarded two grants for further development.
- MIT IMPACT Program: The approaches developed through the M+Visión Catalyst Program were adapted to support career and research development for postdocs at MIT.

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.

As reported in a recent publication in the *Journal of Dental Research*, Professor Han and his team have introduced a new method that enables infiltration of therapeutic molecules (dental resins) deep into the human teeth enamel, which is the hardest tissue found. Infiltration of various molecules and fluid into the enamel could be useful in applications such as enamel restoration and teeth whitening. According to the team, one can achieve deep infiltration of dental resin into human enamel by invoking electrokinetic flow via a small DC voltage. Unlike pressure-driven flow, electrokinetic flow is not dependent on pore size, which enables appreciable flow even through the narrowest nanopores of teeth enamel. The group's paper prompted a discussion with Colgate Inc. for a potential research collaboration, which is currently being planned.

Professor Thomas Heldt leads the Integrative Neuromonitoring and Critical Care Informatics Group. The Heldt group is leveraging multivariate bedside monitoring data and mathematical models to understand the physiology of the injured brain, to improve diagnoses, and to accelerate treatment decisions for the critically ill. During the 2014–2015 reporting period, the group expanded its data acquisition and data archiving infrastructures from the Beth Israel Deaconess Medical Center to Boston Children's Hospital and the Boston Medical Center. These prospective data collection efforts now cover a wide range of clinical conditions (hydrocephalus, severe traumatic brain injury, subarachnoid hemorrhage, brain tumors, and elective neurosurgeries). Furthermore, they encompass the full age spectrum of patients with neurological injuries, with recordings from small children and adolescents mainly occurring at Boston Children's Hospital and recordings from older adolescents and adults taking place at the Beth Israel Deaconess Medical Center and the Boston Medical Center. The resultant database will be unprecedented and is projected to include over 300 patient recordings in the coming two years. The primary focus of work with clinical collaborators in neurocritical care and neurosurgery rests with validating the approach to noninvasive intracranial pressure monitoring. However, the wealth of the collected data also allows for investigation of other aspects of neurophysiology in acutely ill patients, with plans to expand over the coming year.

The group's work in neurocritical care data analytics, pursued in collaboration with their colleagues at MIT's Medical Electronic Device Realization Center, allows them to suggest innovations and improvements in medical device technology. Projects that have application beyond neurocritical care environments revolve around novel ultrasound-based approaches to noninvasive and continuous monitoring of arterial blood pressure and cerebral blood flow velocity.

In collaboration with colleagues from the MGH Department of Emergency Medicine and with funding from the MIT-MGH Grand Challenge in Diagnostics and Japanese medical device manufacturer Nihon Kohden, the Heldt group has begun a new research avenue focusing on early identification of patients at high risk of developing sepsis. Sepsis and severe sepsis have exceedingly high mortality rates yet have been difficult to diagnose. With their clinical colleagues, the Heldt group is developing a database of about 500,000 emergency department admissions to create automated algorithms for flagging at triage patients who are at high risk of having a systemic infection and among whom early therapy should be initiated expeditiously.

Professor Timothy Lu's Synthetic Biology Group seeks to construct and re-encode biological systems from the ground up using synthetic biology, with ultimate applications to understanding how natural biological systems are wired and tackling important real-world situations. In the past year, the Lu group has published five major advances in the field.

Engineering commensal organisms for challenging applications, such as modulating the gut ecosystem, is hampered by the lack of genetic parts. The Lu group has developed a comprehensive genetic toolbox that includes promoters, ribosome-binding sites, and inducible systems for use in the commensal bacterium *Bacteroides thetaiotaomicron*, a prevalent and stable resident of the human gut. The results, published in *Cell Systems*, provide a blueprint for engineering *Bacteroides* for surveillance of or therapeutic delivery to the gut microbiome.

Cellular memory is crucial to many natural biological processes and sophisticated synthetic biology applications. Existing cellular memories rely on epigenetic switches or recombinases, which are limited in scalability and recording capacity. To overcome these limitations, the Lu group engineered the DNA of living cell populations as genomic "tape recorders" for analog and distributed recording of long-term event histories. This platform could enable long-term cellular recorders for environmental and biomedical applications, biological state machines, and enhanced genome engineering strategies.

Current antibiotics tend to be broad spectrum, leading to indiscriminate killing of commensal bacteria and accelerated evolution of drug resistance. As highlighted in *Nature Biotechnology* in September 2014, the Lu group has adapted CRISPR-Cas technology to create antimicrobials whose spectrum of activity is chosen by design. These highly discriminatory, customizable antimicrobials enact selective pressure at the DNA level to reduce the prevalence of undesired genes, minimize off-target effects, and enable programmable remodeling of microbiota.

New strategies are needed to treat infections caused by drug-resistant bacteria. The Lu group created a high-throughput technology to identify combinatorial genetic perturbations that can enhance the killing of drug-resistant bacteria with antibiotic treatment. This technology can be extended to other model organisms, disease models, and phenotypes, where it might accelerate massively parallel combinatorial genetics studies for a broad range of biomedical and biotechnology applications, including the treatment of antibiotic-resistant infections.

Many natural underwater adhesives harness hierarchically assembled amyloid nanostructures to achieve strong and robust interfacial adhesion under dynamic and turbulent environments. Despite recent advances, understanding of the molecular design, self-assembly, and structure-function relationships of these natural amyloid fibers continues to be limited. Thus, designing biomimetic amyloid-based adhesives remains challenging. The Lu group created strong and multifunctional underwater adhesives obtained from fusing mussel foot proteins of *Mytilus galloprovincialis* with CsgA proteins, the major subunit of *Escherichia coli* amyloid curli fibers. This work was reported in the September 2014 issue of *Nature Nanotechnology*.

Professor Rahul Sarpeshkar heads a research group on analog circuits and biological systems. His recent work consists of a pair of papers, "Synthetic Biology: A Unifying View and Review Using Analog Circuits" and "A Cytomorphic Chip for Quantitative Modeling of Fundamental Bio-molecular Circuits," published in *IEEE Transactions on Biomedical Circuits and Systems*. The former paper showed how to map coupled biomolecular differential equations in living cells to pictorial analog circuit motifs that represent them quantitatively. Thus, the mature art of analog circuit design can be mapped to rigorously design synthetic circuits in living cells. The latter paper showed how to simulate highly computationally intensive stochastic biomolecular differential equations at very fast speeds in analog electronic transistor chips, suggesting that large-scale supercomputing simulations of cells may be possible in the future. The results of this research may impact several applications in biotechnology, bio-energy, and medicine affected by the design of synthetic circuits in cells.

Principal research scientist Stefanie Shattuck-Hufnagel investigates the cognitive structures and processes involved in speech production planning, including speech sound sequencing, prosodic structuring, and systematic context-governed phonetic variation as well as speech-accompanying gestures, speech development, and speech rhythm. Her work with speech error patterns and acoustic analyses of prosody and word-form variations has implications for cognitive models of speech production, phonological theory, the development of intervention methods for children diagnosed with speech disorders, and applications in speech recognition and synthesis.

Over the past year Shattuck-Hufnagel and her team continued their experimental work on speech production planning, focusing on several aspects of the processing that language users carry out as they plan an utterance in order to speak it.

- Speech prosody: They showed that listeners judging the alignment of intonation contours with spoken words not only attend to the shape of the pitch rise-fall contour but also weight pitch information differently when it occurs over vowels as opposed to following consonants. This finding is consistent with their model proposing that tonal center of gravity is the critical dimension of tone-text alignment.
- Speech-accompanying gestures: They provided evidence that the grouping of successive gestures is hierarchical in nature, raising the possibility that these gestural structures are correlated with the hierarchical discourse structure of the speech they accompany. This work was presented at the 2014 meeting of the International Society for Gesture Studies in San Diego.
- Speech timing: Analyses of hand movements produced during the tracing of grouped zig-zag patterns do not show the kind of group-final lengthening that is found in speech. This suggests that final lengthening is not a general correlate of motor slowing at the end of a group but, rather, serves as an intentionally produced cue signaling a constituent boundary in structured behaviors such as speech and music performance.
- Speech development: Analysis of children's productions of words with medial or final stops showed that, unlike adults, children produce full stops instead of reduced flaps or glottal stops in these contexts. This evidence supports the

hypothesis that children first produce clear canonical cues to word contrasts, only later acquiring the patterns of simplification and reduction of adults.

- Models of speech perception: In their ongoing work testing Kenneth Stevens's model of feature-cue-based speech perception, they found evidence that the abruptness of onset of frication noise influences listeners' perceptions of the distinction between sounds such as /sh/ and /ch/, offering support for Stevens's characterization of abrupt spectral changes as the foundational cues to the features of words and their sounds in continuous speech.

Dr. Shattuck-Hufnagel undertook two book contracts: *Speech Timing: How Does It Work?* with Professor Alice Turk of Edinburgh University (Oxford University Press) and *Prosodic Theory and Practice* with Professor Jonathan Barnes of Boston University (MIT Press).

Professor Collin Stultz and the Computational Biophysics Group are focused on developing an improved understanding of disease processes at the molecular level and using these new insights to build novel therapeutic tools. Their approach involves building computational/theoretical models and conducting biochemical experiments designed to test and refine these models. The group's research is concentrated in two broad areas. First, they have developed a deep interest in understanding the structure of intrinsically disordered proteins that play a role in neurodegenerative disorders. The ultimate goal of these studies is to use this improved understanding to design molecules that prevent the neurotoxic aggregates that are formed from these proteins. Second, they strive to develop automated computational tools that can identify patients at increased risk of death after adverse cardiovascular events (e.g., heart attack, stroke).

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 CO_2 concentrations as a function of time in exhaled breath. Earlier work of the group, with major participation from Dr. Baruch Krauss at Boston Children's Hospital, used machine learning methods on capnograms to distinguish patients with chronic obstructive pulmonary disease from those with congestive heart failure, and from healthy subjects, on the basis of data collected in a noninvasive and effort-independent manner during a few minutes of breathing. Over the past year, this work has been augmented through the development of a simple mechanistic compartmental model that can be used to estimate physiological parameters of the lung from capnograms. A paper describing the use of such a model to enable tracking of reversible pulmonary obstruction will be presented at the IEEE Engineering in Medicine and Biology Symposium in Milan in August 2015.

The capnography research is currently being extended in the doctoral work of Rebecca Mieloszyk, supported by RLE's Helen Carr Peake Fellowship and co-supervised by

Professors Heldt and Verghese, with the guidance of Dr. Krauss and the participation of undergraduate student Margaret Guo. The work addresses monitoring during procedural sedation. Using data collected by collaborators at hospitals in Canada and Italy, the team has shown that selected features extracted from capnograms cluster in different regions or states, with transitions between states corresponding to events such as administration of a bolus of sedation agent or the start or end of the procedure. Preliminary results will be presented at the 2015 Engineering in Medicine and Biology Symposium.

In an MEng thesis by Max Dunitz, who is co-supervised by Professors Heldt and Verghese, machine learning methods and multiparameter intensive care unit data from the MIMIC II database are being used to predict high lactate levels (a marker for septic shock) from standard monitoring information. The results obtained with the test data exceeded the performance of previously reported methods.

Professor Verghese has recently completed an innovative textbook with Professor Alan Oppenheim, *Signals, Systems and Inference* (Pearson), intended for upper-level undergraduates and beginning graduate students. The book folds together deterministic and stochastic models, concepts, and tools to provide the basis for canonical applications in communication, control, signal processing, and other areas.

Professor Joel Voldman's research interests focus 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, neurons, and stem cells. The group reported on a microfluidic device able to pair immune cells and then study their interactions over time as the immune response develops, allowing the first investigation into how information flows through immune cells from first contact to outcomes hours later. The second area of research focused on microsystems for human health, with work on point-of-care diagnostics and neural probes. Professor Voldman and collaborators have been developing a microfluidic system able to assess the activity of white cells from blood, enhancing traditional measures that enumerate cells by also describing what the cells are doing. Over the past year, Professor Voldman and colleagues at Brigham and Women's Hospital have begun the first measurements of this device with blood from septic patients, potentially providing a bedside monitor of the immune system.

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.

During the last year, the group made several significant advancements:

- They developed a technology that allows rapid generation of genetically engineered *C. elegans*.
- They demonstrated 3D laser micro-patterning of complex vasculature and protein cues that can control guidance and homing of cells in three-dimensionally defined locations inside tissue.
- They developed a high-throughput technology to rapidly map 3D positions of every developing brain neuron in zebrafish disease models of human neurological disorders.
- They developed a technology to perform large-scale in vivo electrophysiology recordings.
- Using non-integrating mRNA reprogramming technology, they developed an ultra-high-throughput technique to rapidly screen combinations of transcription factors to differentiate and generate dopamine neurons lost in Parkinson's disease.

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 researches methods of nanofabrication and implements these methods to develop quantum technologies and nanotechnologies. The main focus is on nanosuperconducting technologies for radiation detectors, quantum circuits, high-speed superconductive electronics, and energy systems. His group has recently overcome the long-standing challenge of understanding and controlling the superconducting behavior in thin films used as the platform for nanodevices. In thin films, the superconducting transition temperature—a significant parameter for superconducting devices—is usually suppressed with respect to the bulk. Despite the scientific and technological interest in finding the parameters that determine this suppression, contradicting models and experimental data have hindered the development of the field by keeping these parameters elusive. The Berggren group found that the transition temperature in the films scales with two parameters, the film thickness and the characteristic electrical resistance at the non-superconducting state. Discovering this scaling helped control the superconducting behavior of films, increasing the yield and performances of the devices. This discovery also allowed the Berggren group to determine low-temperature properties by performing simple low-cost room temperature measurements. Moreover, they demonstrated that almost all other known superconductors follow the same scaling by testing the scaling against the existing literature data.

Further investigation of the discovered universal scaling showed that superconductors are classified according to their morphology, namely granular versus amorphous. Hence, by controlling the morphology of a superconductor, one might optimize the superconducting behavior to specific technological needs. The Berggren group is now working to demonstrate that such optimization is indeed possible. In addition to radiation detectors, optimized superconducting nanostructures can be used in other fields such as quantum computing and energy systems. They can also help to understand the fundamental behavior of superconductors.

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 development an ultra-fast photodetector with the highest reported responsivity based on a graphene heterostructure integrated into an on-chip platform compatible with integrated circuits, the development of techniques for the scalable integration of superconducting nanowire single-photon detectors and quantum memories into photonic integrated circuits, the creation of secure quantum communication using a novel high-dimensional encoding scheme that allows multiple secure data bits for every detected photon, the development of a theoretical proposal for universal quantum computing based on quantum walks and high-fidelity quantum information processing on semiconductor photonic circuits, and the demonstration of a new spectroscopy technique that achieves high spectral resolution. Among various research programs, 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,” that includes five PIs 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 nanometers. 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 multimaterial fibers offer unprecedented control over material properties and function on length scales spanning the nanometer to kilometer range. On the single-fiber level, the group is exploring various opportunities to harness fiber fluid instabilities to produce novel fiber devices. These fluid instabilities are achieved through capillary breakup of localized domains in an otherwise continuous fiber. This approach allows the capability to generate millions of discrete devices in a fiber. A few paths were explored, namely the isothermal approach, where the fibers were isothermally heated and the capillary breakup spontaneously occurred, and the thermal gradient “dripping faucet,” where the fibers were heated in a directional flame. A laser-induced capillary breakup was recently added to the toolkit. The laser setup consists of two lasers with different wavelengths, one mainly absorbed by the fiber cladding and the other mainly absorbed by the fiber core. Thus, high controllability and accuracy of the temperature profile is obtained. Silicon-in-silica sphere generation was experimentally demonstrated.

Additionally, Fink's team expanded the variety of materials and structures available for multimaterial fiber device fabrication by exploring the solidification front propagation in Ge-Si spheres theoretically and experimentally. They were able to make this process controllable and experimentally demonstrated the fabrication of a heterostructured in-fiber sphere, also referred to as Janus particle, made of two semiconductors: silicon and germanium. Also, a ladder-like structure within fiber was demonstrated and characterized in both polymer-clad and silica-clad fibers. The team developed a method called "selective breakup" in which the whole fiber is heated but only the semiconductor core breaks into spheres, while other conductive cores remain in their original continuous shape. The formed spheres were not only distributed periodically but also were able to connect with the conducting wires, hence forming a "ladder-like" structure.

In addition to exploration of fiber fluid instabilities, the group demonstrated the fabrication of a crystalline silicon-core and silica-clad fiber out of an aluminum-core and silica-clad preform. This fiber fabrication is fulfilled with an in situ redox reaction during the thermal drawing process. The ultra-high temperature of the drawing process helps induce the chemical reaction between the aluminum core and surrounding silica, and the difference between the density and the solubility of silicon and another byproduct, alumina, causes the two materials to separate, producing a pure crystalline silicon core fiber.

The research of Professor Jing Kong and the Nano-Materials and Electronics Group focuses on the challenge of combining the synthesis and fabrication of individual carbon nanotubes and integrating them into electrical circuits. 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 (CVD) 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. Together with Professor Evelyn Wang's group in the Department of Mechanical Engineering, the team grew CVD graphene on Cu heat pipes; in addition, they investigated water condensation on Cu/graphene surfaces and obtained not only improved performance but also much more stability. By using "seeding promoters," the group achieved high-quality MoS2 synthesis and developed both vertical and lateral heterostructures of MoS2 with other 2D materials. Their graphene-MoS2 lateral structure was found to be very useful for wideband photo detection. Finally, Kong and her group successfully synthesized large-area, few-layer MoTe2 on SiO2/Si substrates.

In addition to the applications just described, the group is developing low-cost graphene strain/pressure sensors to be used in "vacuum insulation panels" for the thermal insulation for buildings. Also, they have been collaborating with Professor Shadi Hasan's group at the Masdar Institute and have found some unique advantages for wastewater treatment technology. They hope to continue this investigation in the coming years.

Professor Yang Shao-Horn's research programs are centered on understanding the electronic structures of surfaces, with an 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.

Oxide materials are critical components in technologies such as gas sensing, water purification, and (photo)electrocatalysis. Professor Shao-Horn's group has shown intrinsic properties of oxide surfaces that can bridge wetting and activity for oxygen electrocatalysis in aqueous solutions. Their work is the first to report that the receding contact angle reflects the degree of H-bonding with the hydroxylated oxide surface. The study also indicates that simple measurement of the receding contact angle on smooth, oriented thin film surfaces may provide a first estimation of the extent of hydroxylation. This understanding suggests that the design of catalysts should consider chemistries that are intrinsically hydrophobic in nature, with low or moderate tendency to hydroxylate.

The Shao-Horn group, for the first time, obtained the experimental electronic structure in $LaMO_3$ perovskite oxides (M = Cr, Mn, Fe, Co, Ni) by combining information from x-ray emission, absorption, and photoelectron spectroscopy. Through first-principle density functional theory simulations, they identified complementary hybridization features present in the transition metal and oxygen x-ray emission spectra. They then developed a method for self-consistent alignment of the emission data onto a common energy scale using these features, providing a valuable supplementary technique to photoelectron spectroscopy for studying the partial density of states in perovskites.

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 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 nanofabrication, nanocharacterization, and prototyping facility. Also, he leads the Organic and Nanostructured Electronics Laboratory and co-directs the MIT-Eni Solar Frontiers Center. Professor Bulović's research interests include studies of the physical properties of organic and organic/inorganic nanocrystal composite thin films and structures and the development of novel nanostructured optoelectronic devices.

This year Bulović and his colleagues from the School of Engineering, School of Science, and Sloan School of Management completed the "Future of Solar Energy" study, which is the latest in the MIT Energy Initiative's "Future of" series. Its predecessors have shed light on a range of complex and important issues involving energy and the environment, and similarly the Bulović group's study is receiving significant attention. Solar energy is one of the few renewable, low-carbon resources with both the scalability and the technological maturity to meet the ever-growing global demand for electricity. Among solar power technologies, solar photovoltaics (PV) are the most widely deployed, providing 0.87% of the world's electricity in 2013 and sustaining a compound annual growth rate in cumulative installed capacity of 43% since 2000. Given the massive scale of deployment needed, the study and accompanying articles by Bulović and colleagues (examined potential limits of PV deployment at the terawatt scale, emphasizing constraints on the use of commodity and PV-critical materials as well as the challenges encountered by the grid systems accommodating solar installations. Among the many conclusions, the work proposes material complexity as a guiding framework for classifying PV technologies and presents a comprehensive analysis of the three core themes that will focus future research and development: efficiency, use of materials, and manufacturing complexity and cost.

Professor Peter Hagelstein and his team focus their research on applied problems associated with PdH and PdD as metal hydrides. The team carried out an assessment of the equation of state of H2 and D2 at high pressure in order to understand models of fugacity, needed to understand the statistical mechanics of metal hydrides, and they found an error in a widely used model. Models exist for both H2 and D2; they found that the difference between the best two models is not consistent with experiments. Additionally, they innovated a new kind of statistical mechanics model for interstitial H and D in palladium that includes a description of both octahedral and tetrahedral site occupation. Professor Hagelstein used this model to analyze an important older data set for H and D solubility in palladium in the alpha phase. The group was able to develop empirical model parameters that provided the best fit for the data over a wide temperature range, and they extracted solid estimates for T-site energy levels (which had not been done previously).

The new statistical mechanics models with both O-site and T-site occupation for PdH and PdD are perhaps this year's most interesting results. Historically these systems were the first to be analyzed, and the early models perform very well at low temperatures and low loadings. What happens in other regimes has been recognized to be much more complicated. The group's new models make this complicated picture very simple.

The new statistical models are useful for modeling PdH and PdD, especially in high temperature and low loading regimes and at high loading near room temperatures. In the future, the group expects the models to find their way into textbooks.

Principal research scientist Kyung-Han Hong leads the development and applications of next-generation strong-field lasers in the Optics and Quantum Electronics Group, headed by Professor Franz X. Kaertner. Dr. Hong's accomplishments span a range of topics in ultra-fast laser science, nonlinear optics, and high-intensity laser-matter interactions. His research has focused primarily on ultra-short pulse amplification and its application to high-field physics such as high-order harmonic generation (HHG) and relativistic optics. He is also active in a wide range of ultra-fast optics research topics such as ultra-short pulse generation and measurement techniques in the x-ray, ultraviolet (UV), visible, near-infrared (NIR), mid-infrared (MIR), and terahertz ranges. Dr. Hong has focused on three research topics this year.

The first research topic involves the demonstration of a high-flux soft x-ray HHG source driven by a high-power MIR optical parametric chirped-pulse amplifier (OPCPA) operating at a 1 kHz repetition rate. Hong's team generated, via HHG, coherent soft x-rays in the water-window region, which is crucial for biomedical phase-contrast imaging. In addition, the team upgraded the picosecond pump laser and achieved record-high pulse energies from a picosecond solid-state laser amplifier.

The group's second research goal has been the study of femtosecond filamentation phenomena pumped at an MIR wavelength. Using their OPCPA, the team demonstrated three-octave spanning super-continuum generation in a CaF_2 plate and sub-two-cycle pulse self-compression in a ZnS crystal. Furthermore, the group demonstrated MIR filamentation in air, only the second time this has been done.

The group's third research topic has been the optimization of HHG efficiencies using multi-color synthesized optical waveforms. This theoretical work has been done through a collaboration with C.D. Lin's group at Kansas State University. Recently the collaborative research has revealed how to generate bright, low-divergence, soft x-ray high harmonics in a hollow-core fiber using synthesized waveforms.

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. Their experiments have 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. Recent successes in major optical clock and optical arbitrary waveform programs 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. Studies of nonlinear optics in TiO_2 nanostructures are also being pursued in collaboration with Professor Eric Mazur's group at Harvard. TiO_2 is of interest for 1.5-**μm wavelength** nanophotonics because of its compatibility with silicon processing and its immunity to two-photon absorption in that wavelength range. In addition to direct characterization of the ultra-fast nonlinear index of refraction, third-harmonic generation (conversion from infrared to green) was observed and is being studied in waveguides designed for higher order mode phase matching.

Work on optical combs has been synergistic with research in the Center for Ultracold Atoms (CUA) and is being considered for use in high-resolution laser radar (LIDAR) work at Lincoln Laboratory. Femtosecond fiber and waveguide laser work, in collaboration with Professor Kaertner, is motivated by the signal processing demands of LIDAR and radar applications and by the timing precision required by 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 Soljacic work together as a team in the area of nanophotonics. They are enthusiastic about their recent experimental observation of Weyl points in 3D photonic crystals. Much of the recent excitement about topological phenomena in condensed matter systems has been centered around systems that contain Dirac points: conical (linear) dispersions in 2D k-space. Many interesting properties of graphene come from the fact it has Dirac points. However, these are 2D systems, so it is natural to ask what are their 3D analogues? Weyl points are a 3D analogue: they are conical (linear) dispersions in 3D k-space. Among many other important features, material systems that comprise Weyl points can exhibit a variety of interesting topological phenomena. Given the recent renaissance of topological physics, the interest in Weyl points has been growing ever more rapidly in recent years. Despite this huge interest, however, all of the publications regarding them have been theoretical until now. In February 2015, Joannopoulos and Soljacic made the first public announcement of an experimental observation of Weyl points.

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 Soljacic, 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, water window XUV generation, and single-cycle pulse generation. The Kaertner group has observed indirectly subcycle optical field emission from a nanoplasmonic field emitter array at room temperature and within ambient conditions by detecting the carrier-envelope phase sensitivity of the emitter current. A nano-emitter array that can emit electrons through 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.

In a five-year effort, the group has observed 400 eV photons generated with 2-mm, 40-fs, 2-mJ laser pulses; 400 eV photons are in the so-called water window, where carbon absorbs and water is transparent. Based on such radiation, one can construct a soft x-ray microscopy for live cell imaging with nanometer-scale resolution in water, which is very important for biology. However, the flux of the source needs to be increased by a factor of 1,000 for effective imaging modalities.

The Kaertner group has generated single-cycle pulses in mid-infrared through optical difference frequency generation of the light emitted at 800 nm and a powerful 1-mm picosecond laser in periodically poled lithium niobate crystals. Single-cycle mid-infrared sources are important for spectroscopy in this wavelength range as well as for strong-field physics studies.

Professor Leslie Kolodziejski, in collaboration with Professor Michael Watts, is considering the use of rare-earth-doped oxide photonic devices for integration with silicon-based electronic integrated circuits. The oxides that are under exploration include aluminum oxide and titanium oxide deposited via a reactive-ion-assisted sputtering method; the sputtering tool is load-locked, is maintained under high vacuum pressure conditions, and can deposit onto 200-mm wafers or multiple smaller diameter wafers. When the oxide is sputtered along with rare earth elements such as erbium, ytterbium, or thulium, the optical properties of the oxide material are modified. The material properties, or structure-affected properties, that are engineered include the refractive index, the thermal expansion coefficient, optical loss, and optical gain. Having the capability to affect optical loss (minimizing loss at wavelengths of interest) and yet modify optical gain allows for the integration of photonic devices, such as lasers, with CMOS-based integrated circuits. Using waveguide-based structures designed with suitable optical confinement and optical pumping from external diode lasers, lasing is achieved at operating wavelengths of 1,550 nm and integrated within compatible CMOS-based electronic circuits. The deposition parameter space for the various oxides is under investigation, and material characterization is under way.

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 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.

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 Watt has applied these results to chip-based LIDAR, 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 Watts 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.

Professor Paola Cappellaro leads the Quantum Engineering Group, which investigates the dynamics and control of quantum systems to build novel devices that exceed the power of their classical counterparts, with applications in quantum computation, simulations, and sensing.

In the past year, the group achieved enhanced sensing and control of individual electronic spin defects in diamond by exploiting their entanglement with nearby nuclear spins. By entangling electronic spin with a nuclear spin qubit ancilla, the group experimentally demonstrated protection against naturally occurring dephasing noise, extending the electronic spin qubit coherence time by three orders of magnitude without employing any active controls to decouple the qubit from noise. The result was also the first implementation of a feedback control algorithm with an electronic spin qubit. Since precise knowledge of the coupling between the electronic spin and the nuclear spin is essential to using the nuclear spin as an ancillary qubit, the group precisely characterized the transverse hyperfine coupling. For the first time, they performed this measurement for a single spin, harnessing enhanced forbidden transitions during resonant driving. These results will enable use of the nuclear spin qubits as a resource in many quantum algorithms, with enhanced speed and fidelity of control. Because of its quasi-one-dimensional geometry, a versatile system for quantum simulations is the nuclear spin in crystals of fluorapatite. With collaborators, the group measured for the first time the spin diffusion coefficient in these crystals, which show different behavior than more isotropic 3D systems. In addition, they used multi-pulse control sequences to simulate the effects of a noisy magnetic field on the coherence and transport properties of linear spin chains in fluorapatite.

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. In the past year, the group has 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, which have been reported in *Physical Review Letters*, utilize ideas from discrete time signal processing and are shaping the creation of a new field of quantum signal processing.

Professor Terry Orlando and research scientist Simon Gustavsson 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. Over the past year, the focus was on three projects done in collaboration with Dr. William D. Oliver and his team at MIT Lincoln Laboratory.

The superconducting transmon qubit is a quantum LC oscillator with the inductor replaced by a Josephson junction. The nonlinearity of the Josephson inductance renders the oscillator weakly anharmonic, which allows selective addressing of individual energy transitions and, thus, makes the device well suited for investigating multilevel quantum systems. The energy decay and the phase coherence of the first five energy levels of a transmon qubit embedded in a three-dimensional cavity were investigated in the first project. Professor Orlando and Dr. Gustavsson have developed a pulse sequence that sequentially populates/depopulates the higher levels of the qubit, allowing for measurements of decay and coherence and application of dynamic decoupling protocols to each of the individual qubit transitions. They found that the decay times remain in excess of 20 μs for all states up to the fourth energy level, making them promising resources for quantum information processing applications. This work was published in *Physical Review Letters*.

In the second project, Professor Orlando and Dr. Gustavsson systematically studied the first-excited-state population in a 3D transmon superconducting qubit. They found that the excited-state population was consistent with a Maxwell-Boltzmann distribution. The results suggest that both the residual excited-state population and relaxation times may be limited by quasiparticles. This work was also published in *Physical Review Letters*.

In the third project, Professor Orlando and Dr. Gustavsson studied an inductively shunted flux qubit (which was co-invented in the group). This is a complementary approach to the capacitively shunted transmon qubit, which has been studied extensively over the last eight years. Instead of shunting the qubit junctions with a large capacitance, as is done for the transmon, the junctions are shunted by a high-inductance superconducting nanowire. The group has performed initial spectroscopy experiments on an L-shunted flux qubit coupled to a microwave resonator and demonstrated that the device is a viable alternative to the transmon qubit.

Both in the lab of Professor Orlando and Dr. Gustavsson and elsewhere around the world, there has been tremendous improvement in coherence times and the achievable gate fidelities of superconducting qubits. These systems are reaching a level of perfection at which one can realistically envision quantum information processing and quantum sensing applications in the next decade.

Professor Jeffrey Shapiro and Dr. 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 extended the photon-efficient imaging technique, called first-photon imaging and reported in *Science* last year, to array-based detection, promising significant speed-up in practical laser-radar acquisition times. The new algorithm is capable of reconstructing centimeter-accurate 3D and high-resolution reflectivity images at extremely low light levels, at which the average number of photons detected is close to one per sensor pixel.

A second area in which the Shapiro-Wong group scored a major accomplishment this year was an experimental demonstration of the signal-to-noise advantage of entanglement-based quantum sensing over the best classical system in target detection. In quantum illumination, part of an entangled beam is sent to a target embedded in a noisy and lossy environment, while the other part of the beam is retained for a joint quantum measurement with the weak returned light to determine the presence of the target. Conventional wisdom suggests that classical methods would be better in noisy and lossy situations because entanglement is fragile and is destroyed in such environments. Led by research scientist Zheshen Zhang, the experiment demonstrates the contrary—that quantum-enhanced techniques can still be useful in a lossy and noisy environment, suggesting potential entanglement-based applications in practical situations.

The third significant achievement of the team is a collaboration with a group at Columbia University in which the goal is to generate two-photon entangled frequency combs that can be used for high-dimensional encoding in quantum communication. The results, recently published in *Nature Photonics*, verified two of the group's theoretical predictions made more than a decade ago: the periodic revival of two-photon quantum interference and the "collapse" of spectral spread.

Personnel

Elfar Adalsteinsson, Luca Daniel, and Jing Kong were promoted to the rank of full professor. Professor Adalsteinsson is a world leader in the development and application of magnetic resonance imaging. The primary goal of his research is to advance MRI physics and engineering as a means of developing new methods and instruments that can be deployed in clinic settings. Professor Daniel works on computational techniques for modeling and design of complex systems, including microsystems (e.g., integrated circuit modeling and design) and biomedical applications (e.g., electromagnetic analysis for magnetic resonance imaging). Professor Kong is an expert on the synthesis of low-dimensionality (1D and 2D) materials using chemical vapor deposition.

Michael Watts was promoted to the rank of associate professor with tenure. Professor Watts is a leader in the area of integrated photonics and is especially known for his work in silicon photonics, a growing technology with major implications for communications, high-performance computing, and optical sensing and displays, among other areas.

Cathy Borgesen (assistant fiscal officer), Fionnuala Coary (financial assistant), and Elizabeth Cook (strategic initiatives project manager) joined RLE headquarters. Joseph Foley was promoted to assistant fiscal officer, William Gibbs to project mechanic, Tina Gilman to project manager, Albert McGurl to facilities officer, Jason O'Connell to Mechanic A, and Matthew McGlashing to Mechanic B. During the year, Elizabeth Cook and Emily Wilkoff (fiscal officer) transferred to other opportunities outside of the RLE headquarters office.

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

- Professor Emeritus Shaoul Ezekiel, an MIT alumnus who spent 46 years at the Institute as a professor in EECS and the Department of Aeronautics and Astronautics, passed away in January; he was 79. Known to all as Ziggy, Professor Ezekiel's contributions to MIT and RLE spanned five decades. He was an exemplary teacher, researcher, colleague, and friend to many.
- Professor Emeritus John G. King '50 (PhD '53), an experimental physicist and leader of the MIT Molecular Beams Laboratory in RLE for 42 years, passed away in June 2014, at 88. An innovative researcher and educator, he was a champion of attacking science problems with "ferocious vigor."

Faculty Honors and Awards

Professor Anantha Chandrakasan was elected to the National Academy of Engineering. Professor Chandrakasan, the Joseph F. and Nancy P. Keithley Professor in Electrical Engineering and head of the Department of Electrical Engineering and Computer Science, was recognized for his work on the development of low-power circuit and system design methods.

Professor Mildred Dresselhaus was among 19 winners of the Presidential Medal of Freedom, the nation's highest civilian honor. Professor Dresselhaus received the award at a White House ceremony on November 24, 2014. The Presidential Medal of Freedom is presented to individuals who have made especially meritorious contributions to the security or national interests of the United States, to world peace, or to cultural or other significant public or private endeavors. Professor Dresselhaus also received the 2015 IEEE Medal of Honor for her leadership and contributions across many fields of science and engineering. She is the first woman to receive the organization's highest honor since its inception in 1917.

Professor James Fujimoto won the prestigious Frederic Ives Medal/Jarus Quinn Prize from the Optical Society. This award was presented to Professor Fujimoto for "pioneering the field of optical coherence tomography (OCT) and for leading the field to widespread medical application and major commercial impact." Professor Fujimoto also received an honorary doctorate degree at the Nicolaus Copernicus University in Poland. He was awarded the university's highest academic distinction, doctor honoris causa, in "recognition of his contribution to the fields of biomedical optics and medicine, his training and mentoring of young scientists, and his service to the international scientific community."

Professor Qing Hu has been named a distinguished professor of electrical engineering and computer science. Professor Hu has made significant contributions to physics and device applications. Also, Professor Hu was selected by the Optical Society as the 2015 recipient of the Nick Holonyak, Jr. Award. He was recognized for his pioneering contributions to high-performance THz quantum-cascade lasers and their applications in imaging and sensing.

Professor John Joannopoulos was the recipient of the Max Born Award presented by the Optical Society. The Max Born Award recognizes contributions to physical optics. Professor Joannopoulos was recognized for numerous contributions in the area of nanophotonics, including pioneering the "numerical experiments" approach to nanophotonics. Professor Joannopoulos was also awarded the American Physical Society's 2015 Aneesur Rahman Prize for Computational Physics, given annually in recognition of "outstanding achievement in computational physics research."

Professor Tim Lu won the 2015 *ACS Synthetic Biology* Young Investigator Award. This award recognizes the contributions of scientists who have made major impacts in the field of synthetic biology early on in their careers. Additionally, Professor Lu received the 2015 *Biochemical Engineering Journal* Young Investigator Award. This award recognizes outstanding contributions to the field of biochemical engineering by a young community member.

Professor Muriel Médard's group recently won two best paper awards at the 2015 International Conference on Communications in London. The winning papers were "Optimization-Based Linear Network Coding for General Connections of Continuous Flows" (by postdoctoral fellow Ying Cui and her coauthors) and "Linear Network Coding and Parallel Transmission Increase Fault Tolerance and Optical Reach" (by Admela Jukan and Xiaomin Chen).

Professor Rajeev Ram was the recipient of a Professor Amar G. Bose Research Grant. With the support of this grant, named for the founder of the Bose Corporation and a longtime member of the MIT faculty, Professor Ram aims to develop a 100% efficient LED via light from ambient heat.

Professor Yang Shao-Horn has been named the W.M. Keck Professor of Energy. In addition, Professor Shao-Horn has been appointed as a fellow by the Royal Society of Chemistry and the American Association for the Advancement of Science.

Professor Jeffrey Shapiro, Dongeek Shin, Ahmed Kirmani, and Vivek Goyal received the Best Paper Award at the 2014 IEEE International Conference on Image Processing in Paris for "Computational 3D and Reflectivity Imaging with High Photon Efficiency." The researchers developed a low-light imaging algorithm that is similar to the first-photon algorithm but can be naturally and efficiently applied with array-based sensing.

Professor Marin Soljacic was recognized by the Blavatnik Family Foundation and the New York Academy of Science for his exploration of nonlinear optical phenomena and his work on wireless energy transfer using magnetic fields.

Professor Collin Stultz was the recipient of this year's Steven G. and Renee Finn Faculty Research Innovation Fellowship. Professor Stultz is a member of RLE and the Institute for Medical Engineering and Science. A practicing cardiologist, Professor Stultz focuses on "conformational changes in macromolecules and the effect of structural transitions on common human diseases such as Parkinson's and heart disease."

Professor Vivienne Sze received a 2014 Defense Advanced Research Projects Agency Young Faculty Award. Professor Sze's Energy-Efficient Multimedia Systems Group is working to develop technologies that enable energy-efficient and high-performance systems for visual data processing such as video coding, imaging, and computer vision.

The Frank Quick Faculty Research Innovation Fellowship, created through the generosity of EECS alumnus Frank Quick '69 (SM '70), was awarded to Professor Joel Voldman. Professor Voldman's research strives to understand the most basic interactions between single cells, building on various disciplines such as electrical engineering, microfabrication, bioengineering, transport modeling, biology, and medicine.

The Deshpande Center for Technological Innovation at MIT awarded $976,000 in grants to 14 MIT research teams currently working on early-stage technologies. These projects have the potential to make a significant impact on our quality of life. The Deshpande Center, acting as a catalyst for innovation and entrepreneurship, awards grants that fund proof-of-concept explorations and validation for emerging technologies. The projects funded in fall 2014 are as follows.

- Broadband Omnidirectional Antireflection Coating for Silicon Solar Cells Using Guaranteed Global Optimization of Thin Film Optical Coatings (Professor Marc Baldo with Paul Azunre): The design of thin film optical interference coatings remains more art than science. This project is developing the first algorithm that can guarantee that a global solution to a design problem in this class has been found.
- Nanoporous Thin Films for Water Desalination and Purification (Professor Jeff Grossman with David Cohen-Tanugi, Shreya Dave, and Brendan Smith): This project focuses on the development of graphene nanoporous thin films, which promise significant value for the fields of water desalination and filtration.
- A Drug Delivery Platform for Sustained Treatment of Inflammatory Arthritis (Jeffrey Karp and Professor Martha Gray with Tony Aliprantis, Omid Farokhzad,

and Nitin Joshi): This project will create a delivery system for the treatment of inflammatory diseases such as arthritis. The system will release a measured amount of drug in response to the level of inflammation.

- Transparent Displays Enabled by Wavelength-Selective Light Scattering (Professor Marin Soljacic with Chia Wei Hsu): This project explores a new type of transparent display based on the wavelength-selective scattering of light from nanostructures.
- Scalable Photonic Links for Ethernet Systems (Michael Watts with Michele Moresco): This project integrates laser sources with silicon photonics to create versatile and scalable photonic links for Ethernet systems, which will enable unprecedented performance and scalability.

This year the Deshpande Center partnered with the Masdar Institute to support four projects being run jointly by MIT and Masdar Institute faculty. The funding for these projects comes from the Masdar Institute, and $400,000 in funding has been awarded to an RLE project titled Wastewater Treatment: Integration of Electro-technologies and Nanowire Filtration. This project, under the direction of Professor Jing Kong and Shadi Hasan with Wenjing Fang and Sungmi Jung, will focus on the development of a novel wastewater treatment system that combines nanowire filtration and bioelectrochemical treatment for the removal of heavy metals, organic contents, and microbes in water.

Staff Awards

The following RLE community members won 2015 Infinite Mile Awards from the Office of the Vice President for Research: administrative assistant Janice Balzer, assistant fiscal officer Joseph Foley, postdoctoral associate Richard Hobbs, and graduate student Sam Nicaise. Balzer and Foley won as individuals for their unflagging dedication to the individuals they support in RLE. Hobbs and Nicaise won as a team for their work with the RLE Immersion initiative.

Mary Markel Murphy, RLE’s assistant director for administration and human resources, won a 2015 MIT Excellence Award in the category of Bringing Out the Best. Markel Murphy was nominated by RLE headquarters staff and faculty. She was honored for her demonstrated commitment to excellence and commitment to the MIT community.

Student Awards

PhD student Ritchie Chen (materials science and engineering), PhD student Ariel Edward (Ed) Hight (Speech and Hearing Bioscience and Technology Program, Eaton-Peabody Laboratory), and PhD candidate Luke Shaheen (Harvard-MIT Division of Health Sciences and Technology) won 2015 Helen Carr Peake Research Prizes; this prize recognizes outstanding research projects in the area of bioengineering. Chen’s research is supervised by RLE PI Professor Polina Anikeeva. He was recognized this year for his significant discoveries in wireless magnetothermal neuromodulation. Hight, supervised by Professor Christian Brown of the Department of Otology and Laryngology at Harvard Medical School, was honored for his significant accomplishments in advancing the field of auditory prosthetics. Shaheen, supervised by Professor Charles Lieberman of Harvard Medical School, was recognized for his significant accomplishments in developing novel noninvasive diagnostics for subtle acoustic trauma.

The 2015–2016 Claude E. Shannon Research Assistantships were awarded to Gauri Joshi and Arman Rezaee, doctoral students in the Department of Electrical Engineering and Computer Science. These students were recognized for their outstanding research projects in communications. Joshi's doctoral research is supervised by Professor Gregory W. Wornell. Her research focuses on emerging problem areas in contemporary communication and coding arising out of cloud-based infrastructure. Rezaee's research, supervised by Professor Muriel Médard, focuses on novel ways to apply network coding for communications over multicast channels.

Affirmative Action and Outreach Activities

RLE has worked and will continue working to increase the number of women and minorities in career positions in the laboratory. Specific measures will 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 two women to exempt-level staff positions 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 precollege 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 13th year in which CUA 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.

Yoel Fink
Director
Professor of Materials Science and Engineering
Joint Professor of Electrical Engineering and Computer Science