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 supports its researchers by providing a wide array of services spanning financial and human resources (HR), information technology, and renovations. It is fiscally independent and maintains a high level of loyalty from its principal investigators (PIs) and staff. 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 development of best practices at MIT. This new role for the lab is being fulfilled on a number of important fronts. In the past year, 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.

The lab experienced rapid and robust fiscal growth from 2010 to 2014, with its research volume increasing by 50%, making RLE one of the Institute's leading research organizations. With a 2014 fiscal year research volume of $48.7 million, the lab continued to remain strong, reporting slightly reduced spending relative to fiscal year 2013. RLE manages more than 200 active research projects and services for over 70 principal investigators. In fiscal year 2014, nearly 300 graduate students (approximately 225 of whom are research assistants) and 100 undergraduates worked in various labs.

Since 2011, RLE has been endowed primarily by royalties from high-definition (HD) TV intellectual property developed by lab researchers. The proceeds of this endowment are the basis for RLE's discretionary activities and budget. Major research funding is provided by Department of Defense agencies, the National Science Foundation, the National Institutes of Health (NIH), and the Department of Energy (DOE). Additional funding is provided by the government of Madrid, Deutsches Elektronen-Synchrotron (DESY), the Samsung Advanced Institute of Technology, the Skolkovo Foundation, 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 and strategically deploys resources to achieve excellence in research, education, and impact.

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

The lab is home to some of the Institute's most innovative research and strives to develop new administrative approaches and best practices. 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

Figure 1. RLE's approach, from local services to global impact.

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 outlines our approach of generating, disseminating, and preserving knowledge to help solve the world's great challenges.

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. Tables 1 and 2 show a comparison of the overall responses from the last two surveys and illuminate the consistently high satisfaction levels.

Table 1. PI Rating of Very Satisfied / Satisfied

	Quality of Services			Response Time		
Area	**2011**	**2013**		**2011**	**2013**	
Communications, Media, and Design	92%	96%	↑	94%	97%	↑
Information Technology	84%	93%	↑	79%	93%	↑
Facilities/Operations & Space Mgmt.	91%	93%	↑	74%	93%	↑
Fiscal Administration	84%	81%	↔	78%	90%	↑
Human Resources	91%	96%	↑	82%	98%	↑

Table 2. Overall satisfaction level

	2011		2013	
Very Satisfied	22	42%	34	67%
Satisfied	21	40%	13	25%

Goals

Each year RLE focuses on a select group of key initiatives designed with specific objectives in mind. Our 2014 goals centered around five strategic areas: building community, stimulating discovery, developing resources, applying impact, and pursuing quality and efficiency. We are taking active steps and have designed targeted programs to accomplish these goals.

Research and Administrative Initiatives and Events

RLE Immersion

In fall 2013, RLE Immersion was created 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 (See Figure 2) that is incorporated in the marketing for all events, allowing for continuity and providing a framework for the community. The RLE community's response to this initiative has been remarkable: member participation has exceeded expectations.

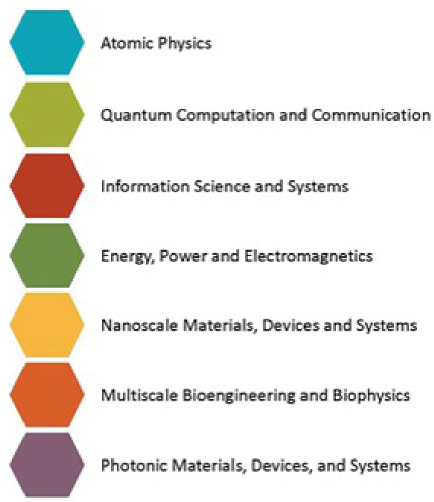

Figure 2. RLE's seven major research themes.

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

Translational Fellows Program

The Institute is committed to generating, disseminating, and preserving knowledge and to working with others to bring this knowledge to bear on the world's great challenges. MIT is a center of innovation and technology with a distinguished legacy of important discoveries that have made a global difference. On an annual basis, approximately 20 start-ups based on research discoveries are created. We wondered whether there were additional measures that could accelerate the research-to-impact translation. Our hypothesis is that the rate of conversion of ideas derived from basic research to products can be significantly increased through deliberate actions.

During 2013–2014, RLE experimented with a new postdoc-based model for the accelerated translation of research-derived technologies. The Translational Fellows Program has the dual goals of accelerating the transfer of these research-derived technologies into commercial products and creating professional development opportunities and jobs for postdocs. This competitive initiative provides funds for its fellows and a yearlong program tailored for value building and aimed at setting the stage for research translation and future venture success. Through this initiative, we hope 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 the 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.

During the final phase of the 2013–2014 experimental year, five TFP fellows each formed their own unique venture. Outcomes include the following: two companies have been started, one project has a research and development (R&D) collaboration, one licensing agreement is pending, and one fellow has accepted a faculty appointment. Fellows reported an increased interest in entrepreneurship as well as benefits to their postdoc research. Across the board, benefits were seen in venture value, professional development, and technology translation. Benefits were also seen in personal satisfaction and skills related to team building.

With the support of the MIT Innovation Initiative, we plan to scale the program to a target of 20 TFP fellows for 2014–2015. We have engaged additional labs and departments, including the Computer Science and Artificial Intelligence Laboratory (CSAIL), the Department of Materials Science and Engineering, the Department of Electrical Engineering and Computer Science (EECS), the Department of Mechanical Engineering, the Microsystems Technology Laboratories (MTL), and the Department of Physics, and have 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 will extend our collaboration with MIT's Venture Mentoring Service facilitating the scale of mentorship, a key aspect of the program, and all fellows will have frequent one-on-one interactions with a mentor. MIT has substantial resources and myriad experts who can help the fellows commercialize their research.

Lincoln Laboratory Collaboration

To promote collaborations and seek funding for joint research proposals, we are matching RLE PIs with key Lincoln Laboratory personnel. RLE is facilitating introductions by sponsoring an initial lunch to be attended by the RLE PI, the RLE director, and the Lincoln Laboratory group head. In 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 gathering data and jointly assessing the renovation process. One of the study's objectives is the creation of a tightly integrated model for renovations that are cost effective and high quality, compliant with safety codes, and have the ability to scale. With 101,000 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. Professor Martin Zwierlein's space for studying ultra-cold atoms has been undergoing a renovation over the past year. In addition, the MIT Department of Facilities has commissioned RLE to expand this study to include three external projects: the renovation of the Kavli Institute, a remodeling of the EECS Building 34 Grier Room conference space, 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 recommended 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 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.

RLE Facilities Tracking System

In January 2014, RLE instituted a central tracking system for issues related to RLE facilities. The system allows the RLE facilities team to track requests for service, permitting visibility into the daily workload of the staff. Since the system's inception, nearly 500 requests for service have been tracked. The system is monitored daily to ensure quality and timely delivery of building operations services by the facilities team. Qualitative data extracted from the system help RLE understand the types of problems and the number of issues submitted by users. RLE uses this information to guide staff training and pinpoint problem areas that can be addressed outside the system.

Postdoc Leadership and Administration Network

Through the Postdoc Leadership and Administration Network, RLE offered a series of workshops to develop the leadership skills of our postdoc community. PLAN allows postdocs to learn, converse, and integrate leadership and administrative skills to help prepare them for becoming faculty or industry leaders. Throughout the year, postdoc trainees attended short courses on communicating technical information to a nontechnical audience, conflict resolution and negotiation skills, and project management. All of the workshops provided practical advice, tools, and techniques for applying best practices in leadership and management.

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

2013 and ended in early June 2014. 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 Stellar course management, audits and compliance, performance reviews, RLE's digital and HR processes, event planning, SAP reporting and processes, fabrication accounts, and Concur travel procedures. Sixteen assistants completed a minimum of 9 of the 12 workshops to receive this year's certification.

Laboratories and Research Highlights

The 2014 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.

The focus of professor Wolfgang Ketterle's research is on the study of the properties of bosonic and fermionic quantum gases. The group uses 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.

The research of professor Vladan Vuletic focuses on how quantum correlations (entanglement) in quantum mechanical systems can be used to overcome various measurement limits and improve atomic sensors or atomic clocks. Professor Vuletic is also interested in exploring the possibility of building a quantum computer, as well as in addressing unresolved questions in quantum mechanics, the measurement process, and quantum correlations between distant particles (nonlocality). This year Professor Vuletic's group reported two breakthrough experiments that were published in *Science* and *Nature*. In the *Science* article, the group reported the first all-optical transistor operated by a single gate photon. Akin to a single-electron transistor where one electron switches a larger electrical current, one gate photon can switch an optical pulse containing several hundred source photons. In their experiment published in *Nature*, Professor Vuletic's group achieved another long-sought goal, the coupling of a single trapped atom to a nanoscopic optical waveguide and the switching of a single atom with a single photon (and vice versa). While the optical transistor and single-photon/single-atom switching at the present stage are proof-of-principle experiments testing physical principles, the realization of the same devices in a solid-state system could enable optical circuits with lower power dissipation than electrical circuits.

Professor Martin Zwierlein's group in experimental atomic physics uses atomic gases at ultra-low temperatures as a universal test bed for condensed matter and nuclear physics. The interactions between the atoms 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-like electrons. Fermions obey the Pauli principle, the constraint that no two fermions can occupy one and the same quantum state. This principle lies at the heart of the periodic system of elements and explains the stability of neutron stars against gravitational collapse; however, when fermions strongly interact, theoretical predictions become extremely difficult. Experiments are needed to uncover how nature deals with this intricate problem.

This year, Professor Zwierlein's group explored nonequilibrium dynamics in superfluid Fermi gases. For the first time, the group was able to track the motion of a single vortex in the superfluid. By changing the interaction strength in the gas and therefore the equation of state of the superfluid, the team was able to vary the vortex period by almost an order of magnitude. The period was shown to be directly tied to the compressibility of the gas. These experiments demonstrated the power of a superfluid hydrodynamics description of even the most strongly interacting Fermi gas known. In further experiments, the team plans to directly study the instability cascade of nonlinear excitations in these systems, from planar solitons to vortex rings into single vortex lines. This research will improve their understanding of nonequilibrium properties of strongly interacting Fermi systems in general, including high-temperature superconductors and neutron stars.

Thus far, experiments on superfluid Fermi gases have relied on point-like "head-on" collisions between atoms. A wealth of new states of matter is predicted when particles have long-range interactions. One highly promising route is the creation of ultra-cold dipolar molecules. In a novel experiment, the Zwierlein group recently created the first ultra-cold gas of fermionic molecules that will be chemically stable in their ground state. The next step is to bring the highly vibrationally excited molecules into their absolute vibrational ground state where they possess a strong dipole moment. This would then allow the formation of a flurry of novel states of matter, from p-wave superfluids to supersolids and quantum crystals. The highlight of this year's research along these lines was the first observation of the singlet and triplet vibrational ground states of these molecules via two-photon spectroscopy. This is the crucial milestone that will enable the formation of molecules in the absolute singlet ground state.

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 Chemistry*) is his group's explanation, together with Troy Van Voorhis in the MIT Chemistry Department, of the mechanism of singlet exciton fission—an ultra-fast process that splits one high-energy excited state into two lower energy excited states. The work may have application to solar cells since it enables the creation of two electrons per incident photon.

Dr. Chathan Cooke has extended his research efforts into the new areas of wireless power transfer for recharging autonomous underwater vehicles while underwater and high-density power distribution for all-electric ships. Also, he has continued in his prior research areas of space-charge imaging by ultrasonics for improved insulating materials and energetic electron and x-ray interactions for biocompatible materials and improved radiation diagnostics.

The wireless power work has achieved over 90% efficient transfer without magnetic materials over substantial separation gaps of almost 20 cm. The goal is to be able to supply power levels of 5 kW and above to recharge battery-powered electric vehicles under the sea or on land. The approach employs dual highly resonant structures, one for transmission and one for the receiver. The structures and impedance levels are optimized to obtain high efficiency, and means to further extend the separation distance will be pursued in the future. More effective wireless power transfer systems are also of value for many other battery-powered applications such as laptops and phones.

All-electric ship power systems are likely to employ DC, rather than AC, in the future due to greater control and stability. However, compact DC power cables and apparatus for the marine environment require new analysis and optimization relative to established AC designs. For example, DC is produced by inverters that also cause high-frequency harmonics, and hence there is a need to design a power apparatus that tolerates the simultaneous DC with AC harmonics. This area of DC power (with harmonics) is rapidly expanding due to other applications such as photovoltaic power sources and large DC loads.

Professor John Kassakian is part of the Laboratory for Electromagnetic and Electronic Systems. Over the past year, his research has focused on developing carbon nanotube–based electrodes for electrochemical double-layer capacitors (EDLCs) and on exploring the effectiveness of EDLCs in combination with Li-ion and NiMH batteries to increase the efficiency of energy extraction. Professor Kassakian's group developed a carbon nanotube growth process that increases the areal density of nanotubes on a conducting substrate by a factor of five. Additionally, they demonstrated energy extraction efficiency improvements for the hybrid EDLC/NiMH and Li-ion energy storage system ranging from 5% to 30% depending on load profiles. Improved EDLCs will have applications in automotive systems, particularly in high-power applications such as regenerative braking. The hybrid system will benefit similar applications.

Professor James Kirtley of the Laboratory for Electromagnetic and Electronic Systems 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, an emulator of a solar photovoltaic source has recently been demonstrated, and a model of a wind turbine system with a doubly fed induction generator is under construction. Also, a single-phase micro-inverter that operates in a fashion similar to a "unity power factor" rectifier has been built.

In addition, Professor Kirtley's team is working on a single-phase induction motor drive system that was invented about 30 years ago by Kirtley and a staff member. A small-scale demonstration of this scheme that replaces the split phase winding and associated capacitor with a rectifier/inverter is under construction. It is believed that this system will afford smaller, more efficient drives for appliances and the possibility of operating at leading power factor.

In collaboration with professor Leslie Norford of the Building Technology section of the Architecture Department and Michael Caramanis of Boston University, Dr. Kirtley is investigating the provision of ancillary services using load response in office buildings by modulating the power input to air-conditioning chiller compressors and charging of electric vehicles. Also, in collaboration with Dr. Mohamed el Moursi of the Masdar Institute in Abu Dhabi, Dr. Kirtley is investigating the dynamics of micro-grids and distributed generation, particularly the effects resulting from power electronics. The small-scale analog micro-grid emulator plays a role in this investigation.

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.

The team's work on compact permanent magnet motors for mobile robots continues in association with professor Jeffrey Lang and a PhD student. Highly advanced hybrid analytical techniques that combine flux tubes with field theory (potential gradient theory) have been developed and are expected to be published soon. A drive motor that achieves a very high torque to weight ratio, suitable for use in a high-speed quadruped robot, has been designed and is to be demonstrated in the next several months. Means for reducing cogging torque in a high-performance motor are under investigation and should produce a motor suitable for a bipedal robot.

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 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 projects' quadruped running robot. The motor should provide similar benefits in any application in which electromechanical concerns are paramount.

Professor Lang and graduate student Matthew D'Asaro have developed a very-low-cost sensory skin that can differentiate between pressure and shear. Applications range from providing a sense of touch to robot hands to the detection of skin damage in prosthesis liners. Work is now under way to improve the sensitivity of the skin and to fabricate it through a wide-area printing process.

A team of graduate students and postdocs under the supervision of Professor Lang and professors Vladimir Bulović and Timothy Swager continue to develop 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 105 or more. The importance of the molecular monolayer is that it prevents contact sticking, thereby eliminating a major roadblock to using the relay for digital logic and radio frequency (RF) switching. Current work focuses on reducing the actuation voltage and simultaneously increasing the ratio of on-state to off-state conduction.

Professor Steven Leeb is part of the Laboratory for Electromagnetic and Electronic Systems, which conducts research in such areas as electronic circuits, components and systems, power electronics and control, micro- and macro-electromechanics, electromagnetics, continuum mechanics, high-voltage engineering and dielectric physics, manufacturing and process control, and energy economics. Professor Leeb's group has had an extraordinary year developing systems for controlling and generating energy. Specifically, Professor Leeb and his team have:

- Developed a new approach for dealing with the "big data" problem of power system monitoring with the introduction of a new high-speed time-series database program called NILMdb. The system has been installed at numerous field sites, including the Ft. Devens Base Camp Integration Laboratory and the US Army Ft. Polk forward operating base training facility.

- Designed an extraordinary 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. The approach preserves convex power point optimization and offers a new level of simplicity and cost containment for solar processing.
- Created a new technique ("switched doubly fed machine") for ship propulsors that requires power electronics rated at only one third or less of full machine shaft power while providing full speed control.
- 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.

Additionally, Professor Leeb and his team spearheaded new research in teaching activities, with funded work to develop new hands-on teaching activities for the EECS teaching laboratories. This work led to a $1 million donation from Cypress Semiconductor Corporation, negotiated by Professor Leeb, which resulted in a space renovation introducing a new prototyping laboratory for students in 38-500 this year. An additional donation of $1.25 million in test equipment was received from Agilent to support this space and teaching facility.

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 a technology for grid-interface power supplies operating at high frequencies. A research program concluded this year demonstrated the use of high-frequency design techniques to realize a grid-interface LED driver that is less than one eighth the size of commercial designs, operates at high efficiency (approximately 93%), and provides high power factor (approximately 0.89) without the use of unreliable electrolytic capacitors. This technology is the subject of a patent filing and has been described in both conference and journal papers, and a follow-on program initiated over the past year is seeking to extend this approach to isolated power converters (e.g., for computer power supplies). A second interesting result has been further development of a switched-capacitor energy-buffering technique that can provide line-frequency energy storage (e.g., for grid-interface power supplies). This work has been patented and licensed to a manufacturer of LED driver power supplies.

Professor Joel Schindall's research includes the invention and development of a nanotube-enhanced ultracapacitor that holds the promise of being superior to electrochemical batteries as a means of efficient regenerative electrical energy storage, and he has also supervised research on dynamic simulation and reliability analysis of complex safety-critical systems. Previous research in the 2003–2010 time frame in Professor Schindall's group verified that ultracapacitor energy storage and power density can be significantly enhanced (3x or greater) through use of electrodes coated with vertically oriented carbon nanotubes rather than activated carbon. This research is presently being commercialized by FastCAP Systems, which was founded by Riccardo Signorelli, one of Schindall's previous PhD candidates. In 2011 and 2012, Professor Schindall worked with SM candidate Matthew D'Asaro to evaluate whether this technology could be applied to microscopic interlaced nanofingers grown on a silicon substrate. If successful, the technology would have the capability to increase both the capacity and frequency response of capacitors used in microelectromechanical systems (MEMS) devices and to provide increased reliability relative to the electrolytic capacitors that are presently the component of choice in this application.

In addition, Professor Schindall is working with PhD candidate David Jenicek to better understand the nanotube array growth process, with the goal of further increasing energy storage density to above 5x, the capacity of commercial activated carbon ultracapacitors. Professor Schindall's group has successfully demonstrated the growth of devices with higher capacitance than electrolytic capacitors of equivalent size. They have also demonstrated that the frequency response is proportional to finger width, which suggests that further increases are possible by utilizing this property. Future applications of this work include the use of interlaced ultracapacitors in MEMS chips for on-chip power conversion and increased reliability through elimination of the need for failure-prone electrolytic capacitors.

Professor David Trumper is a member of RLE's Laboratory for Electromagnetic and Electronic Systems and a professor of mechanical engineering. Over the past year, Professor Trumper and his group have worked on four major projects:

- 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.
- In work with MIT 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 is embarking on a new collaboration with professor Linda Griffith in which they will study tissues such as liver cells in a simulated organ.

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; 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 heterogeneous networks and communication systems and their particular relevance to defense network security and cyber security. Their work extends to applications in satellite, wireless and optical communication, and 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 on 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 chief adviser for the project. Also, six universities in Ireland have joined together to propose a consortium for research on heterogeneous wireless and optical networks; Professor Chan is acting as the adviser for the Science Foundation of Ireland and chairs the review group for the program. These scientific investigations are vital to growing the capacity of the Internet by orders of magnitude in the future, at lower costs per bit and tighter energy budgets.

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. They have developed a new routing and transport layer protocol that is being considered for use for large Internet transactions of the future. Cisco, which also funds the research, has proposed the use of this technology as the protocol for a satellite data network. The protocol is tuned to data centers for big data transport as well. In the next two years, the group will focus on optical networks in fiber and free space for high-speed applications and on satellite networks for global reach, instant infrastructure and disaster relief, and downed network augmentation and reconstitution after cyber-attacks. In the last two years, Professor Chan has chaired a National Science Foundation workshop on terabit networks to set research agendas and has provided input to the Defense Advanced Research Projects Agency (DARPA) and the Office of the Secretary of Defense. In addition, Professor Chan will chair the upcoming Defense Science Board Study on Future Defense Network Architecture in 2015.

The Digital Integrated Circuits and Systems Group, led by professor Anantha Chandrakasan, is involved in the design and implementation of integrated circuits such as ultra-low-power wireless sensors, multimedia devices, and high-performance processors. The group's research spans multiple levels of abstraction ranging from innovative circuit techniques and architectures to algorithms and energy-optimized systems. A key focus is developing energy-efficient integrated solutions for battery-operated systems. The group had major highlights this year in the arena of energy-efficient multimedia applications and communication protocols for wireless sensor networks (WSNs).

The first highlight is an energy- and area-efficient hardware implementation of an inverse transform for high-efficiency video coding (HEVC), developed in collaboration with professor Vivienne Sze. HEVC achieves a 50% reduction in bit rate at the same video quality relative to previous video compression standards such as H.264/AVC. The group has also produced an HEVC decoder integrated circuit. A key feature of HEVC is its large 16 × 16 and 32 × 32 inverse discrete transforms. These large transforms require more computation per pixel and need a larger transpose memory, which affects their area and energy efficiency. In their work, the group proposes and evaluates several techniques to address this issue. The team implements a pipelining scheme to process all transform sizes at a minimum throughput of 2 pixels per cycle with zero column skipping for faster processing (leading to a 27% to 66% lower cycle count). Data gating in the 1D inverse discrete cosine transform engine is implemented to improve energy efficiency for smaller transform sizes (up to 37% energy savings). A high-density transpose memory based on static random-access memory (SRAM) is used for an area-efficient design. This design supports decoding of 4K ultra-HD video at 30 frames per second. The inverse transform engine's specifications are 98.1 kgate logic, 16.4 kbit SRAM, and 10.82 pJ per pixel. Although larger transforms require more computation per coefficient, they typically contain a smaller proportion of nonzero coefficients. Due to this trade-off, larger transforms can be more energy efficient.

The second highlight is a novel communications protocol targeting low-power WSNs, developed in collaboration with professor Muriel Médard. The majority of current wireless communication systems use error correction codes to correct errors introduced during data transmission and error detection codes at the data link layer to prevent propagation of erroneous information to higher layers of the protocol stack by dropping the partial packets. The proposed protocol harnesses information contained in these partial packets and achieves increased energy efficiency and an average network throughput of 35%. The protocol's primary target networks are wireless asymmetric networks (e.g., body area networks), but its use can be easily extended to other types of wireless networks.

Professor Luca Daniel heads the Computational Prototyping Group along with professor Jacob K. White. Their research interests include the development of integral equation solvers for very large complex systems, stochastic field solvers for large numbers of uncertainties, and automatic generation of parameterized stable compact models for linear and nonlinear dynamical systems. During the past year, Professor Daniel and his group had two key research contributions, as follows.

Uncertainties have become a major concern in integrated circuit design. In order to avoid the huge number of repeated simulations in conventional Monte Carlo flows, the group developed an intrusive spectral simulator for statistical circuit analysis. Their simulator employs the recently developed generalized polynomial chaos expansion to perform uncertainty quantification of nonlinear transistor circuits with both Gaussian and non-Gaussian random parameters. They modified the nonintrusive stochastic collocation method and developed an intrusive variant they refer to as the stochastic testing method. In contrast to the popular intrusive stochastic Galerkin method, the coupled deterministic equations resulting from their proposed stochastic testing method can be solved in a decoupled manner at each time point. At the same time, stochastic testing requires fewer samples and allows more flexible time step size controls than directly using a nonintrusive stochastic collocation solver. These two properties make their stochastic testing more efficient than stochastic Galerkin and existing stochastic collocation methods and more suitable for time-domain circuit simulation. They have successfully tested their approach on several digital, analog, and

RF circuits. The archival paper documenting the group's results has had an immediate impact on the community and is now listed as an *IEEE Transactions on Computer Aided Design* "popular paper."

Next-generation magnetic resonance imaging (MRI) scanners will employ large magnetic fields to improve resolution. Unfortunately, the associated undesired electrical fields can induce currents and produce dangerous hot spots. Therefore, accurate and efficient electromagnetic analysis tools are needed in the design of excitation coils to minimize the local specific absorption rate (or heat deposition). The simulated region must include both the coils and a detailed realistic body model. For traditional finite-difference time-domain or finite-element electromagnetic tools, simulating such a large region can take so long (an hour to a day depending on the platform) that coil design exploration is severely limited. The group has instead developed a methodology that performs comprehensive full-wave electromagnetic analysis of arbitrary MRI transmit coils for a fixed realistic body model with a frequency of 2–3 minutes for a typical eight-coil head array in a standard desktop. Their approach is based on a combination of fast integral equation methods and compressed body-model-specific Green functions, and their tools have been proven to be fast enough for use in automated coil optimization and are quickly being adopted by the MRI community, including colleagues at MIT (professor Elfar Adalsteinsson) and Harvard/Massachusetts General Hospital (professor Lawrence Wald).

The research of professor Mildred Dresselhaus and her group focuses on nanostructures to change and control the properties of materials relative to their bulk counterparts. The group uses spectroscopy to study fundamental electronic and phonon properties in novel new materials, with a particular focus on layered nanoscale materials. Professor Dresselhaus and her team have been studying how thermal energy can be used to modify the structure and properties of nanomaterials. Spectroscopy is also being used to study the effects of thermal energy on layered materials. The Dresselhaus team works closely with the Jing Kong group to characterize new materials produced by that group. Professor Dresselhaus also works with professor Gang Chen and a number of faculty and students in his Energy Frontier Research Center in the thermal energy applications area. Professor Dresselhaus and her group have active research collaborations worldwide on these topics with researchers in North America, South America, Asia, and Europe.

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 the synthesis of tailored ultra-permeable membranes for water purification, the development of glass coated with solar thermal fuels that can deice by storing energy from the sun and releasing the energy in the form of heat on demand, and the development of a comprehensive molecular-scale library of the building blocks of fossil fuels along with new ways to use these building blocks directly in devices (e.g., solar cells made directly from coal).

Professor Jae Lim's group is involved in the development of image/video processing methods. Significant results from this year include the establishment of a new inverse filtering method for deblurring blurred images and the development of a new method for lossless compression of images and video.

Professor Muriel Médard leads the Network Coding and Reliable Communications Group, a highly collaborative research group with collaborations that include CSAIL, MTL, the Laboratory for Information and Decision Systems, Lincoln Laboratory, the California Institute of Technology, Boston University, Northeastern University, Stanford University, the Australian National University, KTH, the National University of Ireland Maynooth, Netapp, Alcatel-Lucent, and Technicolor. 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 lossy networks, new algorithms for network inference in life sciences, algorithms for managing throughput-delay tradeoffs, applications of network coding in power line communications, use of network coding in optical 10-gigabit-per-second Ethernet, information-theoretic privacy, information-theoretic approaches to security based on guesswork, and algorithms for operating with sparse data.

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: energy-efficient/adaptive and high-throughput HEVC video decompression for portable multimedia systems and low-power architectures and algorithms for real-time object detection for embedded sensing applications (e.g., security, smartphones). Their work included the world's first published H.265/HEVC CABAC (context-adaptive binary arithmetic coding) entropy decoder, which delivers 5 times higher throughput than the state-of-the-art H.264/AVC CABAC entropy decoder, enabling real-time processing of high-resolution video up to 8 K ultra-HD at 120 frames per second. Additionally, they developed an energy-efficient inverse transform that supports large transforms up to 32 × 32 with minimal hardware cost and that can adapt energy consumption based on video content.

The research of professor Gregory Wornell and his Signals, Information, and Algorithms Laboratory group focuses on "where information meets the physical world." This involves developing efficient algorithmic structures to address emerging problems of fundamental interest involving the manipulation of signals and information in diverse physical settings. Over the past year, their research has concentrated on algorithms and architectures for millimeter-wave imaging, quantum optical communication and secret-key distribution, next-generation data compression, and efficient content streaming over networks.

In the area of millimeter-wave imaging, the group experimentally evaluated their new multicoset array architecture for reducing by orders of magnitude the number of antenna array elements required for high-resolution imaging. These tests, conducted in coordination with Lincoln Laboratory, validated their multicoset array design procedure, their fast algorithm for recovering the active sectors in a sparse scene, and their automated mechanism for detecting false image reconstructions.

With respect to quantum optical communication and key distribution, they have experimentally validated their quantum key distribution (QKD) technology in collaboration with other RLE researchers; they have developed methods for efficient communication in the presence of temporal and spatial crosstalk, which arises due to physical constraints in optical systems; and they have quantified how dark current in practical optical detectors impacts the capacity of optical links.

In the area of compression technology, they have two key results. The first outcome was the development of 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 the model. Moreover, they demonstrated that compression performance was not sacrificed. This new architecture has the potential to lead to a "perpetually upgradable" data compression standard, circumventing important problems with the current compression standards process. It also offers the benefit of allowing compression to be applied after encryption, which is of interest in a number of secure applications. The second key result in the area of compression was development of the fundamental limits of compression of permutations, which is a problem of increasing importance in the design of so-called recommender systems such as Netflix that attempt to use combined input from consumers to rank a variety of products and services.

Finally, in the area of content delivery over networks, they focused on the development of systems with very low delay characteristics, as are required in a rapidly growing number of applications. To this end, they recently developed new, computationally efficient algorithms for streaming that achieve the smallest known delay for a given throughput requirement in packet-oriented unicasting and multicasting networks.

Professor Lizhong Zheng and the Claude E. Shannon Communication and Network Group have been working on applying information theory to a broad range of new problems. The traditional information theoretic analysis is focused on digital communication applications and thus is built on the basic assumptions of reliable, uniform, lossless information processing. In the new era of information processing, the challenge is often how to extract the "useful" information out of a much larger body of data. This requires new analytical tools to understand lossy information processing and to process multiple streams of information with different levels of reliability, as well as the design of tools for algorithms that achieve a good tradeoff between information efficiency and computation complexity.

Professor Zheng proposed a new approach to meeting these challenges: using information geometry to describe general information exchange. With this approach, he and his team established a new metric to measure the efficiency of information exchange that has been applied to solve some long open problems in network information theory and to develop new algorithms to process high-dimensional data such as images and natural language. Professor Zheng believes that a change in research direction will emerge following the group's work in which information theory will be applied to machine learning types of problems, and they are starting exercises in that direction.

Multiscale Bioengineering and Biophysics

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 his group's research in medical imaging with MRI focuses on estimation of brain oxygenation parameters by MRI, parallel transmission technology and applications in MRI, image reconstruction methods for accelerated acquisitions through undersampling, and imaging of the unborn child. In collaborations with colleagues in EECS and at the Massachusetts General Hospital Martinos Center, they proposed and demonstrated a methodology for a comprehensive full-wave electromagnetic analysis of arbitrary MRI transmit coils for realistic numerical body models. Previous approaches required many hours of simulation, and the proposed method is fast enough to be applied in automatic procedures for optimization of coil designs.

Professor Adalsteinsson is associate director of the Madrid-MIT M+Visión Consortium, which recruited the third class of 10 fellows in the past year. The M+Visión fellows are active in several diverse and interdisciplinary research projects in biomedical imaging and technology that cut across imaging modalities. The fellows carry out their research and development to address unmet medical needs with teams of experts in both the Madrid and Boston regions.

Professor Polina Anikeeva and her Bioelectronics Group work on novel biocompatible and minimally invasive materials and devices for recording and stimulation of functional neural circuits. Such devices would potentially enable drug-free therapies for neurological disorders such as Parkinson's disease, spinal cord injury, and major depressive disorder. Her group has developed flexible multifunctional fiber probes for simultaneous neural recording, optical neural stimulation, and drug delivery into the central and peripheral nervous systems. These probes have enabled, for the first time, optical control of motor function in vivo via spinal cord stimulation. The group is currently applying the probes to neural repair with the goal of developing novel prosthetic interfaces for amputees. In addition, the group is developing a minimally invasive approach to implant-free neural stimulation using magnetic nanomaterials targeted to specific cells within the brain. To date, they have demonstrated remote stimulation of deep-brain structures and have developed a technique for independently addressing multiple cell types via functionally decorating them with different magnetic nanomaterials.

The RLE Sensory Communication Group led by professor Lou Braida investigates topics in three broad areas: hearing aids, tactile communication of speech, and auditory-tactile interaction. 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. The long-term goal of the tactile communication research is to develop tactual aids for people who are profoundly deaf or deaf and blind that will serve as a substitute for hearing in the reception of speech and environmental sounds. This research can contribute to improved speech reception and production, language competence, and environmental-sound recognition in such individuals. The long-term goal of the group's research on auditory-tactile interaction is to better understand recent findings that demonstrate improved ability to detect stimuli that are close in frequency when presented simultaneously to the two senses. This research can provide important information about how cues from audition and touch are combined.

Professor Dennis Freeman and the Auditory Physiology Group explore the cochlear mechanisms that underlie the extraordinary properties of the sense of hearing. During the past year, the group discovered that nanometer-sized pores in the tectorial membrane play an important role in determining the remarkable sensitivity and frequency selectivity of the sense of hearing. The tectorial membrane is a gelatinous structure that overlies the sensory cells in the inner ear. The group previously showed that sounds stimulate motions of the tectorial membrane that are transmitted as waves and that the properties of these waves can account for the exquisite frequency tuning of cochlear responses. Work with genetic disorders of hearing now shows that the important wave properties of the tectorial membrane are determined by the interaction of the intrinsic stiffness of the membrane with viscous losses that result from the water that permeates a network of nanometer-sized pores. The tectorial membrane is highly hydrated, with extracellular fluid accounting for 97% of its mass. The remaining 3% is proteins and sugar groups that are organized in a network that resembles the macroscopic structure of a sponge. The sizes of pores in this structure determine viscous losses as waves propagate through the tectorial membrane, thereby determining in turn the spread of excitation and resulting tuning properties in hearing. The group is currently investigating the role of tectorial membrane stiffness and porosity in other genetic hearing disorders, including models of age-related hearing loss. These results could have a significant impact on the clinical diagnosis and treatment of hearing disorders.

Professor James Fujimoto's group performs research in biomedical optical imaging and optical coherence tomography (OCT). The group's research spans technology development, fundamental studies, and clinical applications. They have active 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, Ludwig Maximilians University and Erlangen University in Germany, and the Medical University of Vienna in Austria. 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 imaging at the Harvard Medical School and Boston VA Healthcare System; and pathology 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 clinical 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 recently developed a research prototype instrument for ophthalmic OCT imaging using high-speed vertical cavity surface-emitting lasers created in collaboration with Thorlabs and Praevium Research. The MIT prototype instrument was transferred to the ophthalmology clinic at the New England Eye Center in December 2013, and over 150 patients have been imaged to date. The new technology achieves imaging speeds that are 5 to 10 times faster than commercial ophthalmic instruments. Studies are focused on OCT angiography, a new imaging method that uses repeated scanning and motion contrast to visualize three-dimensional vascular structures without the need for administering angiographic contrast agents. These studies are especially promising because changes in microvasculature in the retina and choroid (the vascular structure behind the retina) are believed to be early markers of disease. Advances are relevant for early diagnosis and for monitoring of disease progression and response to therapy.

The group also developed a research prototype OCT instrument for endoscopic imaging that has been transferred to the endoscopy suite at the Boston VA Healthcare System and has been in use for approximately one year. More than 70 patients have been imaged to date. Studies in this area utilize high imaging speeds to generate high-resolution volumetric imaging of microstructures in upper and lower gastrointestinal pathologies. Studies are ongoing to determine the ability of endoscopic 3D OCT to detect dysplasia in the upper gastrointestinal tract as a means of guiding biopsies and assessing ablative therapies (e.g., radio frequency ablation) for the treatment of dysplasia and cancer.

The group is also working with clinical collaborators at the Beth Israel Deaconess Medical Center to develop nonlinear microscopy imaging methods for assessment of surgical margins in breast cancer surgery. The development of real-time methods to assess surgical margin status has the potential to reduce the rate of repeat surgeries resulting from positive or close margins.

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 fellowship program is the "sandbox" through which she and her team are implementing and adapting a training program that is, in many respects, a radical departure from traditional programs. The M+Visión program has served to train both the fellows and the involved faculty. The 10 fellows in each cohort spend the first four to six months of their fellowship defining and defending a portfolio of translational projects addressing a major unmet medical need and with a high potential for impact. Through this process, 18 projects have been initiated over the past three years. Fellows function, more or less, as PIs and work on teams that include other fellows as well as collaborators they recruit from Madrid and Boston. Despite starting from scratch, many of these projects have already shown sufficient proof-of-concept to begin human studies. In addition, they have already generated dozens of conference and journal publications and considerable intellectual property, and they are beginning to receive external sources of funding. This program and its results have the potential to influence training approaches at MIT and elsewhere. The following are highlights of the projects closest to translation.

- Team Eye: Lack of access to eyeglass prescriptions is the leading cause of uncorrected vision. Team Eye has addressed this problem by inventing a device that, with minimal training, provides a prescription at the push of a button. Based on their very promising clinical trial results, they have founded a company, Plenoptika, and received an India-US grant to develop the technology in partnership with Aurlabs, an Indian company.
- Team Colo: This team is addressing the problem that optical colonoscopy screening is achieving only a 40% reduction in mortality, rather than the expected 90% reduction, because many lesions are missed during the procedure. They have demonstrated proof-of-concept for their novel approach (photometric stereo endoscopy) and are now undertaking human studies.
- Team Cell: Imagine looking at a large number of cells the same way one looks at stars in the sky. This team has found a way to start with a tube of blood, deposit the blood cells in a monolayer on a surface, and then identify the cells of interest with an approach similar to astronomy. As finalists in Mass Challenge, they are now working toward commercializing their technology.
- Team mPET: Through novel algorithms, this team is enabling the use of multiple tracers for positron emission tomography (PET) imaging. This advance has attracted the interest of several commercial entities; licensing discussions are ongoing.

Professor Jongyoon Han and the Micro/Nanofluidic BioMEMS Group focus 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 *Nature Communications*, Professor Han and his group are introducing a novel microfluidic device that enables unique molecular analysis of single cells without disrupting their cellular context. The research team, in collaboration with MIT professor Douglas Lauffenburger's group, developed a multiplexed microfluidic probe for single-cell analysis directly from the standard adherent cell culture and demonstrated that the study of cellular heterogeneity, a concept of intense current research interest, would now be possible. Many physiological and pathophysiological processes are driven by a minority cell group contained in a given tissue/culture, and more specific measurements of molecular signatures of these cells may lead to better understanding and treatment of cancer and other diseases.

The Integrative Neuromonitoring and Critical Care Informatics Group in RLE is leveraging multivariate bedside monitoring data and mathematical models to understand the physiology of the injured brain, improve diagnoses, and accelerate treatment decisions for the critically ill. The group was founded in 2013 when professor Thomas Heldt joined the MIT faculty in EECS and the Institute for Medical Engineering and Science. Prior to joining the faculty, Dr. Heldt was a principal research scientist in RLE, where he cofounded and co-directed (with professor George Verghese) the Computational Physiology and Clinical Inference Group.

With a set of clinical collaborators in neurocritical care and neurosurgery at the Beth Israel Deaconess Medical Center, the Integrative Neuromonitoring and Critical Care Informatics Group expanded the clinical validation of its noninvasive approach to patient-specific and calibration-free estimation of intracranial pressure to patients with subarachnoid hemorrhages. Preliminary results show distinct improvements in estimation accuracy and precision. These results were reported at the 2013 International Conference on Intracranial Pressure and Brain Monitoring and the 2014 annual scientific meeting of the American Association of Neurological Surgeons. Further clinical validation will commence shortly under NIH funding at Boston Children's Hospital, where children with severe traumatic brain injury and hydrocephalus will be studied. Additional validation is planned at Boston Medical Center.

Another major research thrust of the group focuses on predicting clinical deterioration in pediatric patients. The group has been collaborating with members of the Department of Anesthesia, Perioperative and Pain Medicine at Boston Children's Hospital to predict which patients from the regular hospital rooms will need to be transferred to intensive care units. Results from this collaboration are currently being prepared for publication. In addition, the group is collaborating with neonatologists from Boston Children's Hospital and the Beth Israel Deaconess Medical Center to predict deterioration of preterm neonates in neonatal critical care. Finally, a nascent collaboration with members of the Department of Critical Care and the Division of Fetal and Transitional Medicine at Children's National Medical Center in Washington, DC, focuses on the prediction of cardiac arrest in children in cardiac critical care.

Professor Timothy Lu and the Synthetic Biology Group use synthetic biology to construct and re-encode biological systems. In the past year, the Lu group has made five major advances in the field.

Logic and memory are essential functions of circuits that generate complex, state-dependent responses but have not been integrated in single cells. Recently, Professor Lu and his group described a strategy for efficiently assembling synthetic genetic circuits that use recombinases to implement computational logic functions with stable DNA-encoded memory of events. Application of this strategy allowed them to create all 16 two-input Boolean logic functions in living *Escherichia coli* cells without requiring cascades comprising multiple logic gates. The group showed long-term maintenance of memory for at least 90 cell generations and the ability to examine the states of these synthetic devices with fluorescent reporters and polymerase chain reaction. They also created two-bit digital-to-analog converters, which should be useful in biotechnology applications for encoding multiple stable gene expression outputs using transient inputs of inducers. They envision that this integrated logic and memory system will enable the implementation of complex cellular state machines, behaviors, and pathways for therapeutic, diagnostic, and basic science applications. This work was published in *Nature Biotechnology* in 2013 and was followed up with a detailed protocols paper in *Nature Protocols*.

Many natural biological systems—such as biofilms, shells, and skeletal tissues—are able to assemble multifunctional and environmentally responsive multiscale assemblies of living and nonliving components. By using inducible genetic circuits and cellular communication circuits to regulate *E. coli* curli amyloid production, the team has shown that *E. coli* cells can organize self-assembling amyloid fibrils across multiple-length scales, producing amyloid-based materials that either are externally controllable or undergo autonomous patterning. They also interfaced curli fibrils with inorganic materials, such as gold nanoparticles (AuNPs) and quantum dots (QDs), and used these capabilities to create an environmentally responsive biofilm-based electrical switch, produce gold nanowires and nanorods, colocalize AuNPs with CdTe/CdS QDs to modulate QD fluorescence lifetimes, and nucleate the formation of fluorescent ZnS QDs. This work, which lays a foundation for synthesizing, patterning, and controlling functional composite materials with engineered cells, was published in *Nature Materials*.

RNA-based regulation and CRISPR/Cas transcription factors (CRISPR-TFs) have the potential to be integrated for the tunable modulation of gene networks. A major limitation of this methodology is that guide RNAs (gRNAs) for CRISPR-TFs can be expressed only from RNA polymerase III promoters in human cells, limiting their use for conditional gene regulation. Professor Lu and his group have offered new strategies that enable expression of functional gRNAs from RNA polymerase II promoters and multiplexed production of proteins and gRNAs from a single transcript in human cells. They use multiple RNA regulatory strategies, including RNA-triple-helix structures, introns, microRNAs, and ribozymes, with Cas9-based CRISPR-TFs and Cas6/Csy4-based RNA processing. Using these tools, they efficiently modulate endogenous promoters and implement tunable synthetic circuits, including multistage cascades and RNA-dependent networks that can be rewired with Csy4 to achieve complex behaviors. This toolkit can be used for programming scalable gene circuits and perturbing endogenous networks for biology, therapeutic, and synthetic biology applications. This work was published in *Molecular Cell*.

To design and build living systems, synthetic biologists have at their disposal an increasingly large library of naturally derived and synthetic parts. These parts must be combined in particular orders, orientations, and spacings to achieve desired functionalities. These structural constraints can be viewed as grammatical rules describing how to assemble parts together into larger functional units. The group developed a grammar for the design of synthetic TFs in eukaryotic cells and implemented it within GenoCAD, a computer-aided design (CAD) software platform for synthetic biology. Knowledge derived from experimental evidence was captured in this grammar to guide the user in creating designer TFs that should operate as intended. The grammar can be easily updated and refined with increasing experience using synthetic TFs in different contexts. In combination with grammars that define other synthetic systems, the group anticipates that this research will enable more reliable, efficient, and automated design of synthetic cells with rich functionalities. This work was published in *ACS Synthetic Biology*.

Transcriptional regulation is central to the complex behavior of natural biological systems and synthetic gene circuits. Platforms for the scalable, tunable, and simple modulation of transcription would enhance the study of natural systems and the implementation of artificial capabilities in living cells. Previous approaches to synthetic transcriptional regulation have relied on engineering DNA-binding proteins, which necessitate multistep processes for construction and optimization of function. The group has shown that the CRISPR/Cas system of *Streptococcus pyogenes* can be programmed to direct both activation and repression to natural and artificial eukaryotic promoters through the simple engineering of guide RNAs with base pairing complementarity to target DNA sites. The group demonstrated that the activity of CRISPR-TFs can be tuned by directing multiple CRISPR-TFs to different positions in natural promoters and by arraying multiple binding sites in the context of synthetic promoters in yeast and human cells. In addition, externally controllable regulatory modules can be engineered by layering gRNAs with small molecule-responsive proteins. Also, single nucleotide substitutions within promoters are sufficient to render them orthogonal with respect to the same gRNA-guided CRISPR-TF. The group envisions that CRISPR-based eukaryotic gene regulation will enable the facile construction of scalable synthetic gene circuits and open up new approaches for mapping natural gene networks and their effects on complex cellular phenotypes. This work was published in *ACS Synthetic Biology*.

Professor Rahul Sarpeshkar heads a research group on analog circuits and biological systems. His recent work "Analog Synthetic Biology" in *Philosophical Transactions of the Royal Society A* showed that the fundamental laws of noise in gene and protein expression set limits on the energy, time, space, part-count, and molecular-count resources needed to compute at a given level of precision in a living cell. These limits imply that cells must use analog, collective analog, and probabilistic digital strategies to compute; otherwise, even computations of relatively low complexity such as 10-bit-precise addition will not be feasible in the current power and molecular-toxicity budgets of living cells. Therefore, his work shows that analog computation is necessary for the scalability of the field of synthetic biology, which has thus far barely scaled in circuit complexity over more than 15 years. The work also outlines how to use analog computation and analog circuit design to enable synthetic biology to scale in the future. The results of this research have the potential to impact several applications in biotechnology, energy, and medicine that require implementations with few parts and with a small metabolic load to be practical.

Principal research scientist Stefanie Shattuck-Hufnagel investigates the cognitive structures and processes involved in speech production planning, particularly at the level of speech sound sequencing. Her work with speech error patterns and with acoustic analyses of prosody has implications for cognitive models of speech production and phonological theory as well as 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.

- Models of the speech planning process: They demonstrated that sentence-like tongue twisters provoke more serial-ordering errors of linguistic constituents, while list-like twisters provoke more articulatory intrusions, suggesting two separate error-susceptible aspects of the speech planning process. They also developed a model of speech planning based on the cognitive representation of individual feature cues and their parameter values to bridge the gap between abstract phonemic segments and quantitative motor control commands.
- Speech prosody: They showed that listeners weigh pitch cues more strongly in sonorant regions of words and argued for a phonology-based transcription system.
- Speech-accompanying gestures: They provided the first evidence for perceptual groupings of successive gestures based on kinematic similarities in hand shape, trajectory shape, and location with respect to the speaker's body.
- Speech timing: The team marshalled arguments for an extrinsic timing model with three separate processing stages involving phonological planning, phonetic planning, and motor implementation.
- Speech development: They provided evidence for children's manipulation of individual feature cues and developed a new method for testing prosodic development in children with poor motor control by implementing a tool for manual control of resynthesized pitch.
- Models of speech perception: The group took steps to develop Kenneth Stevens's ideas about feature cue perception into a functioning speech analysis system.

In addition, Shattuck-Hufnagel and her group extended their investigations to speech rhythm, showing that speakers with production aphasia have difficulty with rhythm and arguing that (in contrast to many current views) the rhythm of typical speech is not periodic.

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 make sense of multivariate monitoring data collected in acute care settings but also extending to ambulatory care and home monitoring. The group interacts closely with professor Thomas Heldt's research group. Several clinical collaborators also participate in their work.

An important direction of research in the group addresses classification of cardiorespiratory disease states using time-based capnography, which records CO2 concentrations as a function of time in exhaled breath. A paper describing encouraging results from this effort appeared in *IEEE Transactions on Biomedical Engineering* and demonstrated the excellent ability of appropriately processed capnograms to screen patients for chronic obstructive pulmonary disease (COPD) on the basis of data collected in a noninvasive and effort-independent manner and over a few minutes of normal breathing. Similarly, a capnography-based diagnostic test distinguishes COPD patients from those with congestive heart failure with good accuracy. A patent application has been filed.

The capnography research is currently being extended in the doctoral work of Rebecca Mieloszyk, co-supervised by Professors Heldt and Verghese and with the active participation of Dr. Baruch Krauss at Boston Children's Hospital, to address monitoring for asthma severity and during procedural sedation. Dr. Krauss and Professor Verghese also co-organized a very successful two-day Radcliffe Exploratory Seminar in March 2014, "Moving from Reaction to Prediction in Patient Safety Monitoring." The seminar brought together clinicians from a variety of specialties that routinely practice procedural sedation to discuss data collection and processing approaches that could provide better monitoring of patient sedation and cardiorespiratory status. Data collection in support of preliminary studies is now under way at several locations (including in Canada and Italy), following protocols established at the workshop.

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 demonstrated for the first time that AC electric fields can be used to control axonal growth in three dimensions, allowing creation of complex nonplanar in vitro neural networks. This is exciting because changes in network connectivity are thought to underlie a host of complex neurological disorders. The second area of research focused on microsystems for human health, with work on point-of-care diagnostics and neural probes. Professor Voldman and his team have performed their first in vivo studies with a reconfigurable neural probe specifically designed to avoid immune reaction, a significant barrier to creating long-term neural implants. With professor Polina Anikeeva and their collaborators at the University of Washington, they have designed a neural probe that incorporates the latest knowledge in how to avoid glial reactions.

Professor 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. The group also works 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. Although the lab's focus is on investigating neuronal development and regeneration, their high-throughput technologies are applicable to several other fields of investigation in biology.

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, especially as applied to superconductive quantum circuits, photodetectors, high-speed superconductive electronics, and energy systems. His group recently developed a new superconducting circuit element called the nanocryotron, or "nTron." Conceptually, the nTron is the successor to one of the first integrated circuit elements—the cryotron, developed at MIT by Dudley Buck just over 50 years ago. The device seeks to address several of the issues associated with present-day superconducting electronics and is especially promising for applications that require driving high-impedance loads. Additionally, the fabrication of small nTron circuits requires only an electron-beam lithography tool and an etcher, meaning researchers around the world will be able to construct basic superconducting circuits even without access to a specialized foundry. Professor Berggren's group has already used the nTron to demonstrate a set of universal digital operations, as well as pulse amplification with picosecond timing resolution. The group members are working to further develop the nTron for superconducting electronics applications and are also considering applying it to other fields such as photonic quantum computing, superconducting qubits, and single-photon detection.

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 demonstration of a new type of high-speed, high-responsivity photodetector for optical communications consisting of graphene integrated into a silicon photonics platform; the development of high-purity diamond nanocrystals containing nitrogen vacancy (NV) electron spin sensors, resulting in an improvement of approximately two orders of magnitude in nanocrystal spin coherence time; and the development of a new biochemical sensing method based on cavity-enhanced measurement of polymer sensors. Among various research programs, Professor Englund is one of the principal investigators of a major new 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. Recent research highlights include harnessing the inherent scalability of fiber production and an in-fiber capillary instability for the fabrication of uniformly sized, structured spherical particles spanning an exceptionally wide range of sizes. This work was done in collaboration with Dr. Ayman Abouraddy at the University of Central Florida.

The preliminary work on in-fiber fluid instabilities focused on instabilities formed under infinite cylinder limits, practically created via isothermal heating of long sections of fiber in the so-called "Tomotika" regime. The initial results involved polymer fibers with chalcogenide glass cores. This year, the group developed a new approach that incorporates a thermal gradient to produce spheres in a regime similar to a dripping faucet. Importantly, we were able, using this approach, to demonstrate in-fiber spheres in high-temperature systems involving silica and silicon and germanium. The ability to produce small-scale, crystalline silicon spheres is of significant technological and scientific importance, yet scalable methods for doing so have remained elusive. A fiber with dual cores (p-type and n-type silicon) was drawn and processed into spheres. Spatially coherent breakup led to the joining of the spheres in a bispherical silicon p-n molecule, presenting the prospect of creating multisphere meta-assemblies using coherent breakup. The resulting device was measured and revealed a rectifying I-V curve. The results of this work were published in *Nature Communications*.

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.

Professor Yang Shao-Horn and the Electrochemical Energy Group probe the underlying molecular-level mechanisms of catalytic and charge transfer reactions and ion/electron transport and examine the impact of these mechanisms on performance in electrochemical energy devices, including lithium-ion batteries, lithium-air batteries, proton exchange membrane fuel cells, and solid oxide fuel cells. Her recent research is centered on understanding the electronic structures of surfaces/interfaces; searching for descriptors of surface reactivity, catalytic activity, and charge transfer processes; and applying a fundamental understanding to design surfaces for electrocatalysis and for electrochemical energy storage.

Professor Henry I. Smith and his group in the Nanostructures Laboratory (NSL) develop techniques for fabricating surface structures with feature sizes in the nanometer to micrometer range and use these structures in a variety of research projects. NSL is closely coupled to the Space Nanotechnology Laboratory (SNL), with which it shares facilities and a variety of joint programs. The research projects within NSL/SNL fall into three major categories: development of nanostructure fabrication technology; nanomagnetics, microphotonics, and templated self-assembly; and periodic structures for x-ray optics, spectroscopy, atomic interferometry, and nanometer metrology.

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.

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's new nanofabrication, nanocharacterization, and prototyping facility. Also, he leads the Organic and Nanostructured Electronics Laboratory and codirects 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. Collaborative research work involving professor Moungi Bawendi's chemistry lab and Professor Bulović's EECS lab led to the development of very efficient solar cells made of colloidal quantum dots. This work (published in *Nature Materials*) demonstrated room-temperature solution-processed ZnO/PbS quantum dot solar cells reaching a high-power conversion efficiency of 8.55%, as certified by an external testing laboratory. This result has been included on the National Renewable Energy Laboratory chart of verified record solar efficiencies, providing the first data point associated with MIT. The cell was engineered by modifying the band alignment of the quantum dot layers through the use of different quantum dot ligand treatments. Furthermore, the performance of unencapsulated devices remained unchanged for more than 150 days of storage in air. This demonstration introduces a new approach for reaching the goal of high-performance air-stable solar cells compatible with scalable solution processing and with deposition on flexible substrates, as needed for future roll-to-roll solar cell fabrication.

Professor Peter Hagelstein leads the Energy Production and Conversion Group. The group's overall research efforts have included the invention of a semiconductor technology that can allow efficient, affordable production of electricity from a variety of energy sources, as well as continuing investigations of low-energy nuclear reactions. In recent years, the group has focused on coherent energy exchange under conditions where two-level systems with a large energy quantum transfer energy to an oscillator with small characteristic energy. Last year they identified two new physical systems that appear to implement this mechanism, as well as a third system that is a new candidate.

DARPA tasked Professor Hagelstein with exploring the pumping mechanism for the Rhodes group x-ray laser, which the group assumed was to be in the form of a conventional inner-shell collisional or photo-ionization mechanism. A year's worth of analysis showed neither to be viable candidates. However, a new model based on inverse fractionation gives results that seem very closely related to experimental findings. In essence, this important experiment is closely related to experiments showing anomalies in other fields.

In Karabut's high-current glow discharge experiment, collimated keV x-ray emission originating at the cathode surface is observed. Professor Hagelstein and his team interpreted this experiment as due to the inverse fractionation up-conversion of vibrational energy producing excitation of the lowest nuclear excited state. Experiments were carried out at SRI in an attempt to clarify whether this mechanism occurs. The group saw strong charge emission when the foil was driven on resonance. Counts in the low-energy channels were observed with an x-ray detector, reproducibly and correlated with driving on vibrational resonances. In this case the detector is responding to something, but not to keV x-rays in the range for which the detector was designed.

Some Italian researchers carrying out experiments in which large stones are fractured have observed neutron emission, charged particle emission, and elemental anomalies. In the latter case, Fe appears to be lost and new Al to be created. This effect seems closely related to similar elemental anomalies reported in electrochemical experiments, gas loading experiments, and glow discharge experiments. Theoretical conjectures in the literature suggest that this might be due to deformed space time or to disintegration via accelerated electrons. In nuclear physics, incoherent fission is highly nonselective, in contrast to these new experiments, leading Professor Hagelstein and his group to conclude that incoherent fission cannot be a candidate explanation. The group instead proposes fission as a coherent process that is driven by inverse fractionation up-conversion of fracture vibrational energy in the vicinity of the fault plane and that takes advantage of the coupling between vibrations and internal nuclear degrees of freedom recently found by the group.

Finally, the group developed an improved theoretical treatment of coherent energy exchange under conditions of fractionation and found a great deal of interest in this problem at a recent conference, motivating them to put together papers on the model for the mainstream literature.

Principal research scientist Kyung-Han Hong works together with professor Franz Kaertner in the Ultrafast Optics and X-Rays Group. Dr. Hong's accomplishments span a range of topics in ultrafast laser science. His research focuses on ultra-short pulse amplification and its application to high-field physics such as high-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, visible, near-infrared (NIR), mid-infrared (MIR), and terahertz ranges. Dr. Hong has focused on two main projects this year.

The first project involves the development of a high-flux soft x-ray HHG source driven by a high-power MIR optical parametric chirped-pulse amplifier. Dr. Hong and his colleagues completed a femtosecond multi-mJ MIR laser source at a kHz repetition rate, for the first time, using a home-built cryogenic picosecond pump laser and generated coherent soft x-rays. They also confirmed soft x-ray attosecond pulse generation using 3D propagation HHG simulations, opening up experimental soft x-ray attosecond science, which will be experimentally verified next year under Dr. Hong's new research grant from the United States Air Force. In addition, the team uncovered an interesting wavelength scaling feature of HHG efficiency in the multiphoton regime.

The group's second project is the development of a compact terahertz-based electron accelerator. Dr. Hong and his colleagues successfully generated strong single-cycle THz fields using NIR sub-picosecond pulses and then used them to accelerate electrons in free space and in a waveguide. They demonstrated, for the first time, THz free-space electron acceleration and streaking from a conventional photo cathode up to the level of approximately 60 eV and wave-guide electron acceleration of photo electrons using radially polarized THz fields to the level of a few keVs. These revolutionary, compact THz electron accelerators can serve as femtosecond electron guns and eventually substitute for bulky RF-based linear accelerators.

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 temperature in the pulsed mode, the highest operating temperature in the continuous wave mode, and the highest power levels. 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. 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 MIT professors Michael Watts and Franz Kärtner. 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 in 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 Kärtner, 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 Kärtner.

Professors John Joannopoulos and Marin Soljacic work together as a team in the area of nanophotonics. They are enthusiastic about their recent discovery of the angular photonic bandgap concept. The ability to control light has long been a major scientific and technological goal. In electromagnetic theory, a monochromatic electromagnetic plane wave is characterized (apart from its phase and amplitude) by three fundamental properties: its frequency, its polarization, and its propagation direction. The ability to select light according to each of these separate properties would be an essential step in achieving control over light. Tremendous progress has been made toward both frequency selectivity and polarization selectivity. For example, frequency selectivity can be obtained by taking advantage of photonic bandgaps in photonic crystals, while polarization selectivity can be accomplished by means of a “wire grid” polarizer or by exploiting birefringent materials. Methods based on interference and resonance effects have been explored for angular selectivity, but they have limited applications because they are sensitive to frequency. In their work, Joannopoulos and Soljacic tailored the overlap of the bandgaps of multiple one-dimensional photonic crystals, each with a different periodicity, in such a way as to preserve the characteristic Brewster modes across a broadband spectrum. They proved this idea theoretically and realized it experimentally with an all-visible-spectrum, p-polarized angularly selective material system. Their method enables transparency throughout the visible spectrum at one angle, the generalized Brewster angle, and reflection at every other viewing angle.

Professor Steven G. Johnson leads the Nanostructures and Computation Group. Their 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.

Professor Franz X. Kärtner is an RLE principal investigator and head of the Ultrafast Optics and X-rays Division in the Center for Free-Electron Laser Science at DESY Hamburg. This year, his work focused on highly efficient Thz generation and acceleration, high energy pulsed and high average power diffraction limited laser development, compact efficient x-ray sources, femtosecond timing distribution in x-ray free electron lasers, and calibration of astrophysical spectrographs (in collaboration with Smithsonian Center for Astrophysics at Harvard).

Professor Kaertner and his team have made significant research progress during the past year. They demonstrated the first THz-based accelerator producing 7 keV energy modulation on a 50 keV preaccelerated beam as well as a THz gun. The results of this research are currently in preparation for publication in high-profile journals. Additionally, a cryogenically cooled composite thin disk laser with a strict relay imaging cavity has been designed and constructed. Up to 50 mJ pulses at up to a 300 Hz repetition rate have been generated. The concept allows scalability to joule-level pulses at a kHz repetition rate. The group developed a compact inverse Compton scattering source jointly with William Graves and David Moncton from the Nuclear Reactor Laboratory. Also, jointly with the Harvard-Smithsonian Center for Astrophysics, they demonstrated sub-10-cm-per-second calibration of an astrophysical spectrograph with the aim of improving the calibration of HARPS-N (High Accuracy Radial Velocity Planet Searcher for the Northern Hemisphere) in the Canary Islands to the necessary precision for earth-like exoplanet detection.

Professor Leslie Kolodziejski and principal research scientist Gale Petrich, along with her graduate research assistant and in collaboration with professor Michael Watts, investigate the fabrication of optoelectronic devices in III-V compound semiconductors and materials issues related to silicon photonics. Active areas of research include the development of saturable Bragg reflectors for ultra-short pulse lasers and the development of rare earth doped oxides for silicon-based photonic integrated circuits. The latter work provides the optical amplification necessary to overcome the loss associated with routing 1,550-nm-based wavelength division multiplexed optical signals within photonic integrated circuits. Appropriate dopant atoms include erbium and ytterbium incorporated into the deposited oxide with sputtering methods. Al_2O_3 doped with erbium has been deposited and has low optical loss and nanometer-sized surface smoothness with a dopant concentration of 1,020 cm^3. Optical pumping of waveguides composed of Al_2O_3 has created optical gain, and lasing has been observed. Efforts are under way to further improve the material properties and, hence, device performance. By providing optical amplification of silicon-based photonics, integration of Si-based photonic devices with complementary metal-oxide-semiconductor (CMOS)–based electronics is possible.

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 CMOS photonic integration, microfluidic control of cellular metabolism, and thermodynamic limits of optoelectronics.

Professor Ram and his team reported on an energy-efficient photonic modulator in true CMOS. This modulator was integrated with digital circuits to realize optical transmitters that are 10 times more efficient than the previous record. The work was presented at the VLSI Symposium, and the paper was top scored at the 2014 Optical Fiber Conference. Ram and his group also demonstrated the first ion trap implemented in CMOS, and this work was published in *Applied Physics Letters*. This lays the foundation for a new quantum information processing platform. Furthermore, the group initiated a collaboration utilizing their microbioreactors to control the complex genetic circuits developed by professor Tim Lu's Group. This is the basis of the $20 million DARPA InScyT program. Finally, the team demonstrated the first room-temperature light-emitting diode with greater than 100% electrical-to-optical conversion efficiency.

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 (WDM) optical communications, optical phased arrays, optical beam steering, low-phase-noise optical-microwave oscillators, and microwave signal generation.

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 with the goal of building computational and measurement devices that exceed the power of their classical counterparts. To accomplish these objectives, Cappellaro's group follows two directions: a bottom-up approach based on single electronic spins in diamond and a top-down approach in which they study large nuclear spin systems using solid-state nuclear magnetic resonance (NMR) techniques.

In the first approach, the group is studying a diamond defect, the nitrogen-vacancy (NV) color center. NV color centers can be used as building blocks for quantum computation and as sensors for magnetic fields and rotations (in magnetometers and gyroscopes). The focus of the past year has been on studying efficient strategies to reconstruct spectroscopic information of the measured magnetic fields with this quantum probe. In turn, this information can be used to reconstruct the time-dependent variations of the field or their spatial distribution, shedding light on, for example, biological functions or the structure of biomolecules. Magnetic field sensors based on shallow NV defect centers in diamonds have recently detected extrinsic nuclear spins with a sensitivity approaching the single-atom level. The remaining challenge is to resolve contributions arising from distinct nuclear spins in a dense sample and use the acquired signal to reconstruct their positions. Professor Cappellaro's group developed a strategy combining the use of a quantum memory intrinsic to the NV system with quantum control to boost the spatial resolution of NV-based magnetic resonance imaging. The proposed strategy promises to make diamond-based quantum sensors an invaluable technology for bioimaging, as they could achieve reconstruction of the local structure of biomolecules without the need to crystallize them, synthesize large ensembles, or alter their natural environment.

Other research focuses on the precise control of nuclear spins associated with the NV center, which can be used to improve the readout of the electronic spin and for small quantum algorithms. Professor Cappellaro and her team investigated a strategy for indirect control of the nuclear spin, using the electronic spin qubit as an actuator. A key result, obtained using algebraic methods, was finding the time-optimal control solutions for the most general SU(2) synthesis problem and deriving stricter bounds on the time and number of switches required to engineer desired qubit gates via the actuator control. In addition, the group developed new experimental tools to characterize the nitrogen nuclear spin Hamiltonian, devising a method to measure the full hyperfine tensor. This measurement had not been possible until now for single NV centers.

The second approach is to study large quantum systems comprising many nuclear spins via NMR in order to explore coherence properties, control, and noise reduction techniques. In the past year, the group has investigated the nuclear spin systems in crystals of fluorapatite, which is of particular interest since it involves a quasi-one-dimensional geometry and the electronic spin system associated with nitrogen impurities in diamonds, which can be indirectly polarized and probed by the NV center. The dynamics of both systems present complexities due to their many-body interactions. It is of particular relevance to study their coherence properties and how active control can improve them.

Professor Isaac Chuang's group is studying theoretical and experimental quantum information science, and over the past year the team has published a new quantum algorithm for performing inference on Bayesian networks. This algorithm provably achieves a square-root speedup over the best possible classical algorithm for the same problem. Chuang's group has also designed and realized unusual trapped ion chips, including one using graphene in collaboration with professor Jing Kong's group and one fabricated entirely on a commercial CMOS line, at IBM, in collaboration with professor Rajeev Ram's group and a team at Lincoln Laboratory. These advances represent the first steps toward integration of devices and optics for large-scale quantum computation with trapped ions.

Professor Terry Orlando and research scientist Simon Gustavsson direct a multi-university, multidisciplinary research effort focused on using superconducting circuits for quantum computation. The team also studies nonlinear dynamical systems in the crossover regime from classical to quantum behavior. During the past year, research proceeded along two thrusts: they continued to advance techniques for quantum control and noise spectroscopy in superconducting flux qubits, and, in addition, they continually improved the quality and coherence times of superconducting transmon qubits coupled to microwave resonators. This research is in collaboration with Dr. William D. Oliver and his team at Lincoln Laboratory.

Their research on quantum control involved developing pulse sequences aimed at probing the properties of the random processes in the environment that limit qubit performance. Understanding the origin of the noise is essential, both when implementing new quantum control protocols and when designing and fabricating next-generation devices.

The work on superconducting qubits coupled to microwave resonators involved both planar, on-chip resonators and three-dimensional microwave cavities. For two-dimensional systems, the group was able to enhance coherence times by an order of magnitude by improving the circuit design and fabricating the devices using highly defect-free epitaxially grown materials. For three-dimensional systems, the group focused on reducing the effective temperature seen in the qubit by improved shielding, thermalization, and filtering. The group was able to reduce the thermally excited qubit population to 0.1%, allowing the qubit to be almost perfectly initialized in its ground state.

In addition, Professor Orlando and Dr. Gustavsson investigated the dynamics of nonlinear microwave resonators in collaboration with professor Jonas Bylander and his group at the Chalmers University of Technology in Gothenburg, Sweden. The nonlinearities make the devices sensitive to small changes in their operation parameters, allowing them to be used as highly responsive read-out devices for superconducting qubits. This collaboration led to a joint publication in the *New Journal of Physics*.

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. A premier achievement from this year's work—done in collaboration with the group of Dr. Vivek Goyal—was their demonstration, published in *Science*, of first-photon imaging. This new laser-radar technique permits high-quality range and reflectivity images to be obtained with only one detected photon per pixel, whereas conventional systems would require tens to hundreds of detections per pixel. First-photon imaging achieves its remarkable performance by respecting the physics of single-photon detection in the presence of background light, exploiting the spatial correlations that exist in natural scenes, and deriving its range and reflectivity images from computationally efficient convex optimizations.

A second area in which the Shapiro-Wong group scored a major accomplishment this year was high-dimensional quantum key distribution. QKD allows two geographically separated users to create a shared set of completely random key bits in a manner that precludes an eavesdropper from having any information about them. The key rates of existing QKD systems, however, fall well short of what is needed for widespread application because each detection yields at most one quantum bit. The group published a report in *Physical Review Letters* this year that provides a rigorous security proof for a QKD system that extracts multiple quantum bits from each detection of an entangled photon pair and uses a Franson interferometer to provide the necessary security check. In work now under consideration for publication, they experimentally demonstrated a photon-information efficiency of 7 bits per pair detection after 20 km of propagation through optical fibers, which is more than 20 times that of state-of-the-art entangled photon QKD, and a secure-key rate as high as 7.1 Mbps, more than 500 times better than the state of the art.

Personnel

Thomas Heldt, formerly an MIT principal research scientist, was named an assistant professor in the Department of Electrical Engineering and Computer Science. Heldt's research strives to enhance patient monitoring, improve clinical decision making, and provide a better understanding of physiological and pathophysiological processes. He develops and uses mathematical models derived from physiology, along with signal processing and estimation methods, to extract relevant information from clinical data, with applications to cardiovascular and cerebrovascular critical care.

Yang Shao-Horn is the newest member of RLE, having joined the lab in December 2013. Professor Shao-Horn's research focuses on the underlying molecular-level mechanisms of catalytic and charge transfer reactions and ion/electron transport. She examines the impact of these mechanisms on performance in electrochemical energy devices, including lithium-ion batteries, lithium-air batteries, proton exchange membrane fuel cells, and solid oxide fuel cells.

Professor Vivienne Sze joined RLE in August 2013; she is an assistant professor in EECS and a member of the Microsystems Technology Laboratories. Professor Sze's research focuses on the joint design of algorithms, architectures, and circuits to build energy-efficient and high-performance systems.

Karl Berggren, Jongyoon Han, Joel Voldman, and Lizhong Zheng were promoted to the rank of full professor of electrical engineering.

Martin Zwierlein was promoted to full professor of physics.

Jason O'Connell (service mechanic) and Emily Wilkoff (fiscal officer) joined RLE headquarters. Joseph Foley was promoted to senior financial assistant. Rachel Smederovac was promoted to human resources administrator. Victoria Moore (fiscal officer), Rita Patel (fiscal officer), and Justin Wade (assistant director for finance and sponsor relations) left RLE for new opportunities.

RLE center administrator Cathy Bourgeois and RLE administrative assistants Tina Gilman and Laura von Bosau were each honored with an MIT Infinite Mile Award.

RLE fiscal officer Cheryl Charles won the MIT Excellence Award for her work involving employee resource groups at MIT. Charles was recognized along with a team of employees from across the Institute who share interests, issues, and a common bond or background. Members of these groups create a positive work environment at MIT by actively contributing to the Institute's mission, values, and efforts specific to inclusion.

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

- Dr. Amar Bose was a pillar of the RLE community, and he served as an inspiration through his teaching and research during his time at the laboratory. He passed away in July 2013 at the age of 83.
- EECS professor emeritus Kenneth Stevens passed away in August 2013. Professor Stevens was a 1999 National Medal of Science recipient who made significant contributions to the field of speech sciences. He was an important part of the RLE community, inspiring many students, collaborators, and colleagues alike.

Faculty Honors and Awards

Professors Marc Baldo and David Perreault were recipients of the Faculty Research and Innovation Fellowship for 2013–2014. This fellowship recognizes senior EECS faculty members for outstanding research contributions and international leadership in their fields.

Professor Vladimir Bulović was appointed as the MIT School of Engineering's associate dean for innovation. Bulović will supervise the School of Engineering's initiatives on innovation and entrepreneurship, as well as oversee the design and construction of MIT's new nanofabrication and nanocharacterization facility.

Professor Luca Daniel received the Summa Cum Laude Merit Paper Award from the International Society on Magnetic Resonance in Medicine in May 2014. He was also presented the IEEE Transactions on Computer-Aided Design Donald O. Pederson

Best Paper Award (along with co-authors Zheng Zhang, Tarek A. El-Moselhy, and Ibrahim M. Elfadel) for "Stochastic Testing Method for Transistor-Level Uncertainty Quantification Based on Generalized Polynomial Chaos."

MIT Institute Professor Emeritus Mildred Dresselhaus was recognized with the Materials Research Society von Hippel Award for her "pioneering contributions to the fundamental science of carbon-based and other low-electron-density materials, her leadership in energy and science policy, and her exemplary mentoring of young scientists."

Professor James Fujimoto was selected for the 2014 IEEE Photonics Award, given in recognition of outstanding achievements in photonics. Professor Fujimoto was cited "for pioneering the development and commercialization of optical coherence tomography for medical diagnostics."

The American Physical Society elected professor Jeffrey Grossman to fellowship status. This honor, which is bestowed on no more than 1% of society members, was in recognition of his outstanding contribution to physics.

RLE principal investigators Qing Hu, Marin Soljacic, and David Perreault were honorees of the 2013 Invented Here! Program. Hu and RLE visiting engineer Alan Lee were awarded the honor for their patent "terahertz lasers and amplifiers based on resonant optical phonon scattering to achieve population inversion." Soljacic and colleagues were honored for "wireless energy transfer across variable distances," and Perreault and colleagues were recognized for their "method and apparatus for a resonant converter."

Professor Daniel Kleppner was awarded the Franklin Institute's 2014 Benjamin Franklin Medal in Physics, recognizing his "many pioneering contributions to discoveries of novel quantum phenomena involving the interaction of atoms with electromagnetic fields and the behavior of atoms at ultra-low temperatures."

Professor Jeffrey Lang was appointed to the Vitesse professorship in electrical engineering and computer science. The Vitesse chair recognizes an EECS faculty member who has demonstrated exceptional commitment to teaching, research, mentoring, and service.

Professor Timothy Lu was selected for a CAREER Award from the National Science Foundation in support of his work to "understand biological cells as state machines leading to insights into natural biological systems and synthetic gene circuits."

Muriel Médard was appointed as the Cecil H. Green professor of electrical engineering and computer science in recognition of her outstanding technical contributions to and leadership in communications, signal processing, and information theory.

Professor David Perreault was appointed as EECS associate department head. Also, Professor Perreault received two awards for papers: the IEEE Power Electronics Society Prize Paper Award for "Evaluation of Magnetic Materials for Very High Frequency Power Applications" (published in *IEEE Transactions on Power Electronics*) and the IEEE

Power Electronics Society Second Prize Paper Award for “High-Frequency Resonant SEPIC Converter With Wide Input and Output Voltage Ranges.”

Professor Rajeev Ram received a 2014 R&D 100 Award for his SiC battery charger for hybrid electric vehicles, which he worked on while at the US Department of Energy’s Advanced Research Projects Agency-Energy. The R&D 100 Awards “identify and celebrate the top technology products of the year.”

Professor Jeffrey H. Shapiro was elected a fellow of the International Society for Optics and Photonics for his achievements in quantum optical communication, the role of turbulence and random media, and laser radar. Additionally, Professor Shapiro was a corecipient of Lincoln Laboratory’s 2013 Best Paper Award for “Reciprocity-Enhanced Optical Communication through Atmospheric Turbulence—Part I: Reciprocity Proofs and Far-Field Power Transfer Optimization” (with A.L. Puryear) and “Reciprocity-Enhanced Optical Communication through Atmospheric Turbulence—Part II: Communication Architectures and Performance” (with A.L. Puryear and R.R. Parenti).

Assistant professor of electrical engineering Vivienne Sze was the 2013 recipient of the Jonathan Allen Junior Faculty Award. The award is named in honor of professor Jonathan Allen, RLE’s sixth director, for his dedication to mentoring and developing junior faculty members. In addition, Professor Sze was appointed as the Emanuel E. Landsman (1958) career development chair.

Dr. Franco N.C. Wong was elected as a fellow of the Optical Society of America in 2014 for his pioneering development and applications of spontaneous parametric downconverter sources of entangled light, including the Sagnac source, single-photon two-qubit quantum logic, and secure communication using quantum illumination.

Student Awards

Doctoral students Sha Huang (electrical engineering and computer science) and Jonathon Whitton (health sciences and Technology) won 2014 Helen Carr Peake Research Prizes; this prize recognizes outstanding research projects in the area of bioengineering. Huang’s research is supervised by RLE PI Jongyoon Han in the Micro/Nanofluidic BioMEMS Group. She was recognized this year for her significant accomplishments in applying microfluidic measurement of red blood cell deformability to the study of malaria and to blood storage lesions. Whitton, supervised by Daniel B. Polley, an assistant professor of otology and laryngology at Harvard Medical School, was honored for his significant accomplishments and promise in studying distractor suppression and enhanced auditory signal processing through immersive “audiogames” and investigating how training with these techniques generalizes to real-world auditory challenges.

The 2013–2014 Claude E. Shannon Research Assistantships were awarded to Mina Karzand and Kuang Xu, doctoral students in the Department of Electrical Engineering and Computer Science. These students were recognized for their outstanding research projects in communications. Karzand’s doctoral research is supervised by professor Lizhong Zheng of the Claude E. Shannon Communication and Network Group. Her research interests focus on wireless systems and on multiple-input/multiple-output channels in particular. Xu is supervised by professor John Tsitsiklis of EECS and the Laboratory for Information and Decision Systems. Xu is examining the effects of flexibility in large-scale stochastic networks, where only very small amounts of resources are flexible enough to serve multiple demand types. His research also focuses on quantifying the impact of predictions and forecasts on the efficiency of flexible systems.

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 has appointed two women to exempt-level staff positions in headquarters.

Cheryl Charles (fiscal officer for HR/payroll administration) attended a leadership program that was offered through The Partnership Inc., an organization that teaches professionals of color how to make the most of each stage of their career and how to expand their leadership capacity.

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 four 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 12th 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