Research Laboratory of Electronics

The Research Laboratory of Electronics was founded in 1946 following the groundbreaking research it conducted leading to the development of Ultra High Frequency Radar, changing the course of World War II. Cognizant of its rich history and focused on maintaining its position as MIT's leading interdisciplinary research organization, RLE fosters a stimulating and supportive environment for innovative research. RLE provides visionary leadership, vibrant intellectual communities, and superior administrative services. Through strategic deployment of resources, RLE offers a supportive environment for achieving excellence in research, education and impact.

The Lab is experiencing rapid and robust growth. Since fiscal year 2010, the Lab's research volume has increased by 50%, making it one of the Institute's fastest growing organizations. With a fiscal year 2013 research volume of $53.2 million representing a 14% increase over 2012, RLE manages over 200 active research projects and services over 70 Principal Investigators. In fiscal year 2013, RLE included 300 graduate students (approximately 225 of whom are research assistants) and 111 undergraduates who worked in various labs.

In 2011, the Lab established an endowment fund which helps fund its discretionary activities. Major research funding is provided by Department of Defense (DOD) agencies, the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Department of Energy (DOE). Additional funding is provided by the Government of Madrid, Deutsches Elektronen-Synchrotron (DESY), Samsung Advanced Institute of Technology, Skolkovo, and the National Aeronautics and Space Administration (NASA). Furthermore, numerous projects are funded through industry and private foundations.

Besides being home to some of the Institute's most innovative research, the Lab 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 spreading across the schools of science and engineering, the Lab is uniquely situated to embrace Institute-wide initiatives. To that end, RLE has engaged in a number of initiatives aimed at organizational improvement including the Low Cost Renovation Study, Translational Fellows Program, Digital RLE, 8th floor café, RLE Research Fair, and Administrative Assistant Certification Program.

The academic year 2013 saw many awards, recognitions and milestones for RLE investigators and striking progress in the research associated with groups and various education initiatives begun within the past several years. The following is a summary of RLE research highlights from the past year.

Atomic Physics

Research in atomic physics at RLE encompasses an investigations in ultracold atoms, quantum condensed gases, and atom optics. New methods are being developed for manipulating and probing Bose-Einstein condensed atomic gases and exploring ultracold 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 ultracold 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, i.e. the ordering of spins. In addition, the group studies ultracold molecules and their reactions.

An important result followed the study of inelastic collisions of ultracold Li2 molecules with itself or Li or Na atoms. So far, such collisions were shown to behave universally, i.e. that their rate is only determined by the electric attraction between the particles. When particles come close, they undergo an inelastic collision with 100% probability. For collisions between Li2 and Li, a much smaller collision rate was found, implying that those particles can reflect off each other without vibrational relaxation of Li2. These findings were published in *Physical Review Letters* (T.T. Wang, M.-S. Heo, T.M. Rvachov, D.A. Cotta, and W. Ketterle. Deviation from Universality in Collisions of Ultracold 6Li2 Molecules. *Physical Review Lett*ers 110, 173203 (2013)).

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, ultracold gases of bosonic and fermionic atoms are quantum fluids, which have properties different form 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 to improve atomic sensors or atomic clocks. Professor Vuletic is also interested in exploring the possibility of building a quantum computer, as well as in exploring unresolved questions in quantum mechanics, the measurement process, and quantum correlations between distant particles (non-locality). This year Professor Vuletic's group reported several breakthrough experiments, two of which were published in *Science*, and one in *Nature*. To begin with, the group reported the first all-optical transistor operated by a single gate photon (Chen et al, *Science* [DOI:10.1126/science. 1238169], 2013). In this experiment, 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 another breakthrough experiment to appear in *Nature*, Professor Vuletic's group reports the demonstration of attractive forces between individual photons, such that two photons are bound together. This very first binding of two photons that was predicted in various systems over the last two decades has never been observed before. The system permits the realization of a quantum gate between two photons, the basic element of an optical quantum computer. Professor Vuletic's group also published another *Science* article on a long-sought goal, the coupling of a single trapped atom to a nanoscopic optical waveguide (Thompson et al., *Science* 340, 1202 (2013)), opening up possibilities for novel quantum devices, and they published two more papers in *Physical Review Letters* on beating the so-called standard quantum limit of measurement. While the optical transistor operated by a single gate photon at the present stage is a proof-of-principle experiment testing physical principles, the realization of the same device in a solid-state system could enable optical circuits with potentially lower power dissipation than electrical circuits. This could represent potentially very important technology for future computers.

Professor Martin Zwierlein's group in experimental atomic physics uses atomic gases at ultralow temperature 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 have to 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 it 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.

Last year, Professor Zwierlein's group had directly observed the superfluid transition in their strongly interacting Fermi gas. Now this year, the group was able to explore non-equilibrium dynamics in these gases. They created solitons, solitary waves that do not spread as they propagate, and watched their subsequent motion in the superfluid. The inertial mass of the solitons was found to be strongly enhanced, more than 200 times their bare mass and 50 times larger than theoretical predictions, a sign of strong quantum fluctuations present in the gas. The experiment thus serves as a benchmark for theories on strongly interacting Fermions, from high-temperature superconductors to neutron stars. The results are published as an article in *Nature* (Yefsah, T. et al., *Nature*, advance online publication doi:10.1038/nature12338, in print July 25, 2013), and highlighted in *Nature* News&Views.

A second highlight of the year was the first direct observation of spin-orbit coupling in a Fermi gas, a major ingredient for novel topological phases of matter. In this system, the motion of atoms is directly coupled to their spin state. The gas can then behave as a spin diode, a one-way street for atoms of given spin: Spin "up" atoms are only allowed to walk one way; spin "down" atoms the other way. The results were published in *Physical Review Letters*, 109, 095302 (2012), and were featured as the Editor's suggestion and in the American Physical Society's journal *Physics* 5, 96 (2012). In the presence of interactions between atoms, this system should form a long-sought-after topological superfluid, whose topologically protected edge modes have been proposed as carriers of quantum information.

Thus far, experiments on superfluid Fermi gases 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 ultracold dipolar molecules. Their interactions are long-range and can be attractive or repulsive depending on the relative orientation of the dipoles. In a novel experiment, the Zwierlein group has recently created the first ultracold gas of fermionic molecules that will be chemically stable in their ground state. To make a fermionic molecule, one must bind a bosonic atom – sodium, for example – to a fermionic atom – like the 40K isotope of potassium. This is exactly what the experimenters were able to do: they cooled a mixture of sodium and potassium atoms down to Nanokelvin temperatures and fused the atoms into NaK molecules without any creation of heat. This result was published in *Physical Review Letters* 109, 085301 (2012) and received the Editor's suggestion. 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.

Ultracold atomic gases represent essentially the basic building blocks of many-body theory. The group can model bosons and fermions in a clean and perfectly controllable environment. Interplay between theory and experiments thus allow novel insights into a vast variety of physics problems, ranging from condensed matter physics to nuclear and astrophysics. In condensed matter physics, for example, the mysteries of high-temperature superconductors, colossal magnetoresistance materials, spin systems and quantum magnetism are not well understood. In nuclear physics, where one aims to recreate the first split-second of the Universe, new forms of matter are found, the so-called Quark-Gluon plasma. This strongly interacting soup of quarks and gluons shares properties with the group's strongly interacting Fermi gas. Additionally, physicists try to understand the nature of distant Neutron stars, extremely dense remnants of a star slightly heavier than our sun, but only ten miles in diameter. Despite the immense difference in density and scale, neutrons are fermions just as the atoms in Professor Zwierlein's experiments, and it is possible to increase the interactions between atoms to be as strong as those between neutrons in a Neutron star. From a table-top experiment, the group can thus learn about the equation of state of distant neutron matter.

Circuits, Systems, Signals, and Communications

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 the 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 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 and development of the "right" network architecture. Heterogeneous networks must provide agile and economical service delivery in the face of challenges that include rapidly changing communication channel quality, link connectivity, and traffic flows. The biggest challenges come from channels with fast time varying properties, such as their capacities, and when the applications require time deadline delivery such as disaster relief and early warning. These scientific investigations are vital to growing the capacity of the Internet by orders of magnitude in the future, at lower cost per bit and tighter energy budgets. In the next two years, the group will focus on optical networks in fiber and free space for high speed applications and also satellite networks for global reach, instant infrastructure and disaster relief down network augmentation and reconstitution after cyber-attacks. In the last two years, Professor Chan has provided input to NSF, DARPA and the Office of the Secretary of Defense ATL for the formulation of future network research that will appear in the 2013+ Congressional Budgets.

The Digital Integrated Circuits and Systems Group, led by Professor Anantha Chandrakasan, is involved with the design and implementation of various integrated circuits ranging from ultra-low-power wireless sensors and multimedia devices to high performance processors. The research spans across multiple levels of abstraction ranging from innovative new process technologies and circuit styles to architectures, algorithms, and software technologies. A key focus of this group is developing energy efficient integrated solutions for battery operated systems. This research group has major highlights this year in the arena of energy efficient radios for communicating medical information around the human body.

The first highlight is an energy efficient 2.4 GHz receiver for Medical Body Area Networks that consumes just 180 pJ/b and runs at 1 Mbps with −67dBm sensitivity. This work combines radio-frequency MEMS resonators into a single system-in-package device that multiplexes the resonators to achieve multi-channel operation. It is the lowest energy receiver among multi-channel narrowband receivers at 2.4GHz. This work was featured in the Radio Frequency Integrated Circuits Symposium and was selected as a student paper finalist (P. Nadeau et al., "Multi-channel 180pJ/b 2.4GHz FBAR-based Receiver," RFIC2012).

The second highlight is an ultra-low power transmitter for body area networks that consumes 440pJ/b for 1Mbps at 2.4GHz (A. Paidimarri et al., *IEEE Journal of Solid-State Circuits*, vol 48, no. 4, pp. 1042-1054, April 2013). This work achieves stable three-channel operation with efficient multiplexing of MEMS-resonator based oscillators. An efficient power amplifier is designed for −10dBm output power and includes integrated pulse-shaping capability for improved spectral efficiency. This work achieves the highest overall efficiency among frequency-stable transmitters in its output power range.

In collaboration with Professor Muriel Medard, the transmitter was integrated with a network coding engine in the first silicon demonstration of Digital Network Coding. Network coding is employed as a low-overhead packet erasure code to improve the range and reliability of sensor-node data transmissions. The engine consumes 15 μW overhead and achieves up to 5.6dB of coding gain. This work received the Best

Student Paper award at the IEEE International Conference on Communications 2013 (G. Angelopoulos et al., ICC2013).

Finally, the receiver and transmitter were combined into a platform demonstration of body area network technology (sensor, processing, and low-energy communication). For an accelerometer application with an average data rate of 2kbps, the heavily duty-cycled radio consumed an average power of just 14 μW, which is within the range of centimeter-sized energy harvesting sources or coin-cell batteries.

Professor Luca Daniel's research interests include development of integral equation solvers for very large complex systems, stochastic field solvers for large number 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 has been refocusing and extending a significant portion of their research efforts from simulation and modeling purely for 'integrated circuits' to simulation and modeling to include the biomedical field. In particular, new collaborations with the groups of Professor Elfar Adalsteinsson (RLE), Larry Wald (Harvard-MGH), Mikhail Kozlov (Max Plank Institute Leipzig, Germany) and Siemens (Erlangen Germany) are now beginning to have an impact with three results accepted in the top annual MRI conference in April 2013 and several journal papers about to be submitted. Specifically, Professor Daniel's group has developed: 1) a new volume integral equation solver for analysis of electromagnetic fields in the human head and body during MRI scans; this specific contribution came more from a postdoc in Jacob White's group; 2) an integral equation electromagnetic field solver exploiting pre-computed head/body MRI specific Green Functions; 2) a technique to compress the representation of the MRI scanning electromagnetic fields inside heads/bodies, in collaboration with Jacob White; 3) a parameterized reduced order models for the impedance of coils in the presence of heads and bodies during MRI scans; and 4) a framework to decouple automatically the arrays for the new generation of parallel MRI transmission coils. These contributions will allow the Adalsteinsson and Wald groups to efficiently explore, in just minutes, thousands of different parallel coil array configurations in order to control and minimize dangerous local heat deposition in the next generation of very high resolution MRI machines produced by Siemens.

Another portion of the research of the group of Professor Daniel has been re-focused to simulation and modeling for emerging technologies (e.g. silicon photonics and CMOS-NEMS). In particular, the group has developed tools that generate "automatically" compact dynamical models for nano-electro-mechanical resonators designed and fabricated in Professor Dana Weinstein's group (MTL). The generated models are suitable for AC, DC and RF operation of the devices and allow circuit/system designers to run circuit-level time-domain simulations using any commercial circuit simulator. The models are "parameterized," so that the circuit designer will be able to instantiate instantaneously models within the circuit simulator for different values of the key device parameters. As a critical contribution, the proposed algorithm guarantees that when circuit designers change arbitrarily values for the device parameters, the generated compact models will always preserve the physical properties of the original device and will never cause numerical instabilities and convergence issues when connected to other device models and circuit blocks within the circuit simulator. As first output of these efforts the group of Professor Daniel has already co-published with Professor Weinstein's group this year; a conference paper and a JMEMS journal paper are currently under review where they have extended their modeling to also capturing thermal sensitivities.

Finally, the group of Professor Daniel still continues some of the original research activities in the more standard integrated circuit applications. In particular, in January 2013, the group resealed on public domain a C++ open source capacitance extraction code CAPLET. The key idea involved developing specialized instantiable basis function templates that moved the computational bottleneck of this integral equation solver from the non-embarrassingly parallelizable matrix solver to the embarrassingly parallelizable matrix setup phase. 90% parallel efficiencies have been demonstrated on tens of cores. "Real-time" capacitance extraction performance has been demonstrated (generate 3D field solver accurate parasitic capacitance values while dragging and stretching wires with the mouse).

Professor Mildred Dresselhaus and her group's research focuses on nanostructures to change and control the properties of materials relative to their bulk counterparts. The group uses spectroscopy to characterize materials and to study fundamental phonon properties, as well as the interaction of phonons with each other and with electrons, and how these excitations change the properties of nanomaterials. In some of their research, the team has been studying how thermal energy can be used to modify the structure and properties of nanomaterials. Structural modifications that they have found to be caused by thermal energy application may have broader scientific impact on materials research. Professor Dresselhaus and her group have active research collaborations worldwide on these topics, with researchers elsewhere in North America, South America, Asia, and Europe. Two highlights from this past year for Professor Dresselhaus were the Fermi Award from President Obama and the Kavli Prize in Nanoscience from King Harald of Norway and Fred Kavli.

The work of Vivek Goyal spans several aspects of information processing. Successful work continues in a variety of areas, including magnetic resonance imaging; optimal decision making under a variety of constraints, especially those related to human cognitive limitations; and design of information representations for networks that combine data acquisition with computation. In the past year, the most prominent lines of work were in explaining certain aspects of human perception, forming images with extremely few detected photons, and low-power 3D sensing to enable free-space gestural user interfaces for battery-powered mobile devices.

A few of the more notable accomplishments: Many aspects of human perception follow logarithmic scaling, where a perceived intensity is proportional the logarithm of a stimulus intensity. This logarithmic scaling is also seen in numerosity — the innate sense of number. While these scalings have been studied since at least the 1860s, Goyal's group provided the first framework for understanding them as optimal under informational constraints. This work was discussed in *The American Scientist*; IEEE Spectrum's Techwise Conversations podcast; and *Significance*, the bimonthly magazine of the Royal Statistical Society and the American Statistical Association. In the imaging arena, active optical systems use narrowband sources and optical filtering along with highly sensitive photon-counting detectors to improve signal detection rates and suppress ambient light. Despite these optoelectronic enhancements, image formation invariably requires detection of many photons for each image pixel, with statistical averaging to enhance signal and mitigate noise. Goyal's group introduced a method to acquire range and reflectance images simultaneously, both from only a single detected photon per pixel location, even in the presence of significant ambient light. The method was experimentally demonstrated in collaboration with the group of Professor Jeffrey Shapiro and Dr. Franco Wong. The unprecedented photon efficiency that they achieved translates to low-power active imagers capable of operating in high-noise environments. Finally, Goyal's group has made significant progress on low-cost, application-specific optical sensing methods. Applications-specific sensing can reduce resource requirements; for example, to track the hands of a user in three dimensions, an imaging device need not first perform the expensive step of capturing a high-resolution depth map. *Focus*, a UK-based science and technology magazine, features a conversation with Goyal on gesture-controlled mobile phones in its "Breakthroughs of 2013" article in the January 2013 issue. Technology from Goyal's group is at the core of 3dim's nascent effort to bring 3D sensing to smart phones, tablets, and wearable computers. The 3dim team won the MIT $100K Entrepreneurship Competition's Pitch Contest and Launch Contest. They also were selected for MassChallenge, which is the world's largest startup accelerator and competition.

Professor Jeffrey Grossman's group focuses 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 design of a graphene membrane capable of desalinating water with a permeability up to 500 times larger than current RO membranes, the prediction of solar cells based on two-dimensional materials with specific power densities greater than any other known energy conversion material, and the first experimental demonstration of a solar thermal fuel they designed based on hybrid nano structures, representing a new material that can absorb and store the sun's energy in the form of heat on demand.

Professor Jae Lim's group is involved in the development of video compression methods. Video compression is used extensively in reducing the required bandwidth in video communication systems and in reducing the required storage in the same systems. Their application focus is on improving digital TV systems. Significant results from this year include development of algorithms in incorporating new transforms for video compression systems. These have the potential to be used for the development of new video compression systems and for efficient transmission of 3-D TV signals.

Professor Muriel Médard leads a highly collaborative research group with research collaborations that include the Computer Science and Artificial Intelligence Laboratory, the Microsystems Technology Laboratories, the Laboratory for Information and Decision Systems, MIT Lincoln Laboratory, the California Institute of Technology, Aalborg University, Boston University, the Budapest University of Technology and Economics, the University of Waterloo, the Australian National University, Stanford University, Rutgers University, Xidian University, KTH, Eurecom, University of Porto, the National University of Ireland Maynooth, the Technical University of Munich, Technische Universitat Carolo-Wilhelmina zu BraunschweigTechnicolor, Alcatel-Lucent, Raytheon BBN Technologies, Orange/France Telecom and BAE. The group's central theme is communications, with a special emphasis on new practical and theoretical developments in the area of network coding. Some specific achievements during the past year include both theoretical and practical work in developing network coding techniques for wireless cellular systems; new analysis and demonstrated code for providing virtual coded TCP; new fundamental results in the area of throughput-delay tradeoffs; new fundamental results in the area of low-SNR wireless capacity; and new theoretical and practical advances in network coding for body area networks.

The research of Professor Gregory Wornell and his group focuses on signal processing, digital communication, and information theory, and includes algorithms and architectures for wireless and sensor networks, broadband systems, and multimedia environments. This last year, their research concentrated in four significant areas: algorithms and architectures for millimeter-wave imaging, coding for emerging distributed storage systems, quantum optical communication and secret-key distribution (QKD), and advanced brain-machine interfaces.

In the area of millimeter-wave imaging, motivated by a variety of emerging commercial applications, they continued to develop new techniques for reducing by orders of magnitude the number of antenna array elements required for high resolution imaging. The new architecture is based on the use of what they refer to as multi-coset arrays, and exploit intrinsic sparseness in the imaging environment. The group's most interesting results for this period include an efficient multi-coset array design procedure, a fast algorithm for recovering the active sectors in a sparse scene, and an automated mechanism for detecting false image reconstructions. In the area of coding for distributed storage systems, Professor Wornell and his group have developed fundamental limits on codes having the property that they can be locally updated and locally repaired. Locally updatable codes require that only a few elements of the codeword change when an element of the encoded data changes, and locally repairable codes require that only a few elements of the codeword are required to recover a corrupted codeword element. In the area of quantum optical communication, they have developed new adaptive PPM methods for high-dimensional QKD, low-density random matrix methods for secret key extraction in high-speed QKD systems, and an efficient layered architecture for large alphabet QKD. Finally, in the area of brain-machine interfaces, the group has demonstrated a design that combines motor target and trajectory intent using optimal feedback control principles. Moreover, they have developed an analysis of their feedback-controlled parallel point process filter for estimating goal-directed movements from neural measurements.

Professor Lizhong Zheng and the Claude E. Shannon Communication and Network Group has been working on applying information theory to several new problems, including quantum communication and wireless MIMO channels. The highlight of their work is the progress on using information geometry to study networks. A complete framework for this study has been developed and found to be particularly powerful in studying “natural” information exchange in general, in contrast to the traditional coded reliable communication modes. Professor Zheng’s new approach allows information theoretical studies to be applied to a broader context, covering machine learning algorithms, finance and energy problems, where new results start to be generated.

Specifically, Professor Zheng and his team have been working on three areas: quantum optical communication, wireless multiple antenna channels, and information geometry for network information theory. In all three areas, they have finished work worthy of a journal publication. Their research in information geometry will lead to new research directions about general information exchange in algorithms. Professor Zheng believes that a change of research direction will emerge following their work, applying information theory to machine learning types of problems, and they are starting exercises in that direction.

Energy, Power, and Electromagnetics

This theme comprises work in excitonics, studies in the absorption and emission of light, solar cells, disordered and low-dimensional materials, complex nanostructures, organic 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 is his group’s demonstration of a solar cell that generates two electrons for every absorbed photon. The device exploits singlet exciton fission. This is a process that splits one high-energy photon into two lower energy photons.

Principal Research Engineer Dr. Chathan Cooke’s research is mainly in three areas: metal-insulator interfaces; energetic electron/photon beam interactions; and DC electric power systems for modern ships. For the metal-insulator interfaces, he has been using a combination of high-resolution ultrasonics to image space-charges near these interfaces and high-sensitivity conduction measurements at high voltages to quantify the terminal currents associated with interface charge accumulations. This work demonstrated the sometimes intense local charges that can disturb the internal stresses (if not controlled) in insulators in electric power systems. This research is supported by industrial sponsor, Toshiba.

In the area of energetic radiation work, electron and photon beams are produced by the group’s Van de Graaff accelerator facility in Building N10, High Voltage Lab. These beams have been applied to develop improved durability of materials for hip and knee implants, working with the MGH Harris Orthopedic Biomechanics and Biomaterials

Laboratory. Additionally, the beam has been applied for hazardous materials identification by nuclear resonance fluorescence, working with Passport Systems Inc., Berkley University Physics, and Pacific Northwest National Laboratory. This work is mainly supported through the US Department of Homeland Security. Furthermore, the beam has been used to calibrate various satellite solar flux detectors, working with satellite instrument companies; and energetic electrons are also implanted into insulators as an effective means to quantify charge transport processes.

The DC power system efforts concern protection systems, including new techniques for DC power breakers, and non-contact charging systems for underwater vehicles. These are needed for handling the increasing requirements for greater amounts of electric power in ocean vessels.

Professor James Kirtley is a specialist in electric machinery and electric power systems. He has made consistent progress on numerous projects over the last year. Of note are his advancement on the small scale microgrid analog simulator; the functioning of the diesel engine driven synchronous machine emulator; and two important modules from Master's thesis projects that are nearing completion - one to emulate a solar panel source and one to emulate a wind turbine generator.

In collaboration with Professor Steven Leeb, analytical and experimental studies of doubly fed induction motors have been carried out. For certain types of drive, such as ship propulsion, they think it possible to take advantage of the characteristics of the load to sharply reduce the rating required for the power electronics system. Their propulsion system would operate with the machine stator being fed by DC for low speed operation and connected to a fixed AC source for high speed operation. Depending on the level of overload torque available, the required size of the power electronics may be only 25% of total drive rating. The trick is making the conversion between low and high speed operation with a minimum of noise and stress on shafting. A solution to this problem is the subject of a paper presented to the Applied Power Electronics Conference. Improvements to circuit breakers for DC power systems, as might be used on a ship for example, have been developed and have been presented to the Electric Ship Technology Symposium (ESTS) in April, 2013.

Distribution systems for electric power continue to be important and interesting source of challenges. In the past year, one of Professor Kirtley's PhD students investigated reliability of distribution systems with redundant transformers, showing that the normal 'N-1' criterion is not sufficient in heavily loaded substations, but that there are adequate ways of analyzing such systems of interconnected distribution transformers. This work was presented to the 2013 International Symposium on Smart Grid Technology (ISGT) in February 2013.

Voltage control on distribution lines with distributed generation connected can be challenging, as distributed generators can produce reverse power flow with the possibility of voltage levels exceeding standard limits. Professor Kirtley and his team have developed a graphical technique for understanding and estimating these voltage issues and have demonstrated ways of optimizing location and ratings of distributed generators. This work was presented to the IEEE Power and Energy Society General Meeting in July 2013.

Collaboration with Professor Jeffrey Lang is continuing, and a highly advanced multi-phase motor for use in joints of mobile robots that was designed last year is to be refined, built and tested with the intention of improving the performance of a quadruped 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/nano-scale electromechanical actuators and sensors, and distributed electromechanical structures.

A team of graduate students and postdocs, under the supervision of Professors Vladimir Bulovic, Timothy Swager, and Lang have recently demonstrated a NanoElectroMechanical relay that operates with an organic molecular monolayer between its contacts. Closing the relay is effected with a 1-V electrostatic actuation. When closed, the relay conducts via tunneling through the molecular monolayer; when open, its conduction reduces by a factor of 10^5 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 RF switching. Work is now underway to reduce the actuation voltage and simultaneously increase the ratio of on-state to off-state conduction.

Together with colleagues at the Georgia Institute of Technology, Professor Lang and his doctoral student Mohammad Araghchini have designed and demonstrated low-profile toroidal air-core inductors. The inductors are manufactured with MicroElectroMechanical Systems fabrication techniques, and are thus suitable for use in integrated power electronics. They typically approach ten millimeters in diameter, and exhibit an inductance near 1μH and a peak quality factor in excess of 20 in the vicinity of 10 MHz. When used in an LED lighting application, they appear to permit a 10-to-100-fold reduction in size of the LED driver, while permitting a simultaneous significant improvement in system efficiency compared to existing commercial drivers.
Professor Steven Leeb is a part of the Laboratory for Electromagnetic and Electronic Systems (LEES). LEES research areas include 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,

- They developed a new technique for sensing current in power system components like circuit breakers without the need for contact with a conductor, and without the need to "surround" a conductor with a toroid or other measuring material. They received a patent on an inductively coupled technique for transmitting information for this and other systems through steel enclosures for nonintrusive measurement without physical penetration.

- Their work on condition-based monitoring for electromagnetic actuators, and particular HVAC system components that consume substantial amounts of building energy, received a prize paper award at the International Compressor Engineering Conference.
- Using a new magnetic sensor, the TMR, they developed non-contact techniques for measuring flow in other utilities, including water distribution systems. This work has led to a preliminary patent filing.
- In collaboration with Professor David Perreault's research group, they developed a new technique for reducing the capacitive energy storage required for grid-tie inverters, essential for introducing renewable energy on to the grid. This work has resulted in three patent filings during the performance period.
- They initiated a new program in DC power distribution protection using a new circuit protection scheme, a modified Z-Source breaker, in collaboration with Professor James Kirtley.

In addition, the group has spearheaded new research in teaching activities, with funded work to develop new hands-on teaching activities for EECS department teaching laboratories. This work has led to a $1 million donation from Cypress Semiconductor Corporation, negotiated by Professor Leeb, for space renovation in Building 38. Additionally, they have developed and demonstrated new techniques for using power system monitoring for vibration detection and are using the techniques to improve the "underway" acoustic signature of USN warships.

Professor David Perreault's research focuses on advancing power electronics technology and in the use of power electronics to benefits important applications. Major research thrusts include the development of extreme high-frequency power conversion to attain miniaturization and integration, development of power converters having greatly improved efficiency, and in the use of power electronics to benefits applications such as solar photovoltaics and LED lighting. During the past year, some of Professor Perreault's focus has been away from MIT, ramping up a startup company focusing on rf power amplifiers for cellular communications; the technology employed is based on earlier work that has been licensed from MIT. One interesting research result at MIT has been in development of new methods for buffering twice-line-frequency energy for interfaces between dc sources and loads and the single-phase ac grid. This is important for applications such as photovoltaic power converters, LED lighting and grid-interfaced power supplies. Multiple methods for addressing the energy buffer issue have been developed. One method focuses on eliminating unreliable electrolytic capacitors from the grid interface through the use of switched-capacitor energy buffers. This work has resulted in three related patent filings and two "in-press" journal publications, and licensing discussions are ongoing with a power electronics manufacturer. A second method focuses on both buffering energy and improving the performance of inverters interfacing to the grid (e.g., for solar microinverters). This work has resulted in an accepted conference paper to appear later this year.

Professor Joel Schindall's research includes the invention and development of a nanotube-enhanced ultracapacitor which 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 could be significantly enhanced (3 times 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 his previous PhD candidate, Riccardo Signorelli. From 2011 through 2012, he worked with MS candidate Matthew D'Asaro to evaluate whether this technology could be applied to microscopic interlaced nanofingers grown on a silicon substrate. If successful, this technology would have the capability to increase both the capacity and frequency response of capacitors used in MEMS devices, and also to provide increased reliability as compared to electrolytic capacitors that are presently the component of choice in this application. In addition, Professor Schindall is currently working with PhD candidate David Jenicek to better understand the nanotube array growth process, with the goal of further increasing energy storage density to >5 times, 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. The future application of this work includes the use of interlaced ultracapacitors in MEMS chips for on-chip power conversion and to increase reliability by eliminating the need for failure-prone electrolytic capacitors.

Professor Markus Zahn and the Continuum Electromechanics/High Voltage Group's research revolves around electromagnetic field interactions with materials and devices. This past year, they have continued their work on three major research projects. The first is the ABB Project in MIT Energy Initiative (MIT*ei*), "Positive and Negative Streamer Initiation and Propagation in Dielectric Liquids." This project concerns the use of COMSOL multiphysics analysis to solve high voltage charge injection and transport in point-sphere electrode geometries that model experimental data taken by ABB Research Ltd., the sponsor of this research. The COMSOL analyses modeled ABB experimental data very well. The second project is funded by Siemens in MIT*ei*, "Dielectric Materials for New Applications," which uses electric field induced birefringence (Kerr Effect) to measure electric field and space charge distributions in a high voltage stressed parallel plate electrode geometry for various combinations of anode and cathode electrode materials and surface treatments. The goal of the project is to raise the electrical breakdown strength of dielectric materials by choosing electrodes that have bipolar homocharge injection so that positive volume charge forms adjacent to the positive electrode and negative volume charge forms near the negative electrode. Such bipolar homocharge distributions have lower electric fields near the electrodes, which allows higher voltage operation without electric breakdown. Kerr electro-optic measurements have shown that those electrode configurations that resulted in bipolar homocharge injection have higher electrical breakdown strengths.

A third project, "Magnet and Magnetic Fluid Configurations for Improved Separations of Magnetic and Non-magnetic Materials," involves a new MIT patent-pending method for magnetic separation of magnetic liquid phase/particles from non-magnetic liquid phase/particles. This has been developed for applications such as cleaning up oil spills by separating oil and water liquid phases or by separating magnetic materials from non-magnetic materials in biomedical and microfluidic applications. This work has developed a method using non-uniform magnetic fields generated by edges of permanent magnets for the magnetic separation of magnetic and non-magnetic materials. This research has also developed improvements to magnetic separation using a one-sided magnetic flux configuration, known as a Halbach array, to increase the efficiency of separations. The end result has been improved magnetic separation methods for oil/water systems to such an extent that it has the potential to be used to limit the damage in future ocean oil well spills. The process will allow the quick and efficient separation of oil from water so that clean water can be returned to the oceans and pure oil, with removed magnetic nanoparticles for reuse, can be transported to a refinery for the usual processing. The group has two patent submissions for this process.

Multiscale Bioengineering and Biophysics

This theme encompasses thrusts in bio-inspired electronics and neural prostheses for hearing and sight; nano- and micro-technologies for understanding and manipulating biological processes at the cellular and molecular level; imaging and computational modeling of disease and neuro-anatomical processes; and communication biophysics, including 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 focus their research on medical imaging with MRI, primarily at the Martinos Center for Biomedical Imaging. Their research activities currently aggregate around a few themes: estimation of brain oxygenation parameters by MRI; development of parallel transmission technology and applications in MRI; image reconstruction methods for accelerated acquisitions and compressed sensing; and recently launched efforts in fetal imaging with Boston Children’s Hospital. A presentation by Audrey Fan at ISMRM described what she has termed Quantitative Oxygenation Venography. She is able to visualize the venous-side vasculature with quantitative estimates of oxygen saturation. Professor Adalsteinsson and his team are excited to further develop and validate these methods since the potential applications impact the evaluation of stroke, tumors, and fetal and neonatal brain development. In addition, Professor Adalsteinsson is also tightly involved with the Madrid-MIT M+Vision Consortium, within which several diverse and interdisciplinary imaging research projects are under way.

Professor Polina Anikeeva, the principle investigator in the Bioelectronics Group at RLE, works 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 multifunctional neural probes for simultaneous neural recording, optical neural stimulation and drug delivery into the brain and spinal cord. Furthermore, the Bioelectronics Group is developing a minimally invasive approach to implant-free neural stimulation using magnetic nanomaterials targeted to specific cells within the brain.

The RLE Sensory Communication Group led by Professor Lou Braida investigates topics in three broad areas: hearing aids, and the tactile communication of speech. The long term goal of the hearing aid research conducted in the group is to develop improved hearing 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 on the fundamental limitations on the improvements in speech reception that can be achieved by processing speech. The long term goal of the tactile communication research conducted by the group is to develop tactual aids for persons who are profoundly deaf or deaf-blind to 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 focus of Professor Bertrand Delgutte's research continues on the neural coding of sound, both in normal hearing animals and in deaf animal models of cochlear implants. The normal hearing work focuses on neural mechanisms for listening in everyday challenging acoustic environments comprising multiple sound sources and reverberation. The cochlear implant work focuses on the effects of onset time and duration of deafness on the neural coding of interaural time differences (ITD), which is the most important cue for sound localization in normal hearing listeners. In research done with postdoctoral fellow Dr. Yoojin Chung and collaborator Dr. Kenneth Hancock, the team showed that the neural coding of ITD with bilateral cochlear implants is severely degraded in congenitally deaf animals compared to animals with normal auditory development. Long-term deafness confined to adulthood had more subtle effects on ITD sensitivity, suggesting that there is a critical period for the experience dependent maturation of binaural circuits in the brainstem. In future studies, they plan to address whether the observed degradation in ITD coding in early-onset deafness can be reversed by appropriate stimulation through the cochlear implants. To address this question, the group has developed a novel, chronic awake rabbit preparation for studies of cochlear implantation that will allow the testing of the effects of auditory deprivation and electric stimulation longitudinally in the same animal. Their findings support bilateral cochlear implantation at a young age in children with early-onset deafness, followed by fitting with a sound processor that delivers effective ITD cues.

Professor Dennis Freeman and his Auditory Physiology Group have been exploring the cochlear mechanisms that underlie the extraordinary properties of the sense of hearing. During the past year, the group discovered a cochlear mechanism that could help to explain the remarkable sensitivity of the sense of hearing. This sensitivity is thought to be driven by electromotility of a special class of sensory receptors known as outer hair cells, which amplify sounds as they propagate through the inner ear. The Auditory Physiology Group discovered that electromotility is not only a property of the sensory receptors, but is also a property of the overlying tectorial membrane. The electromotile response of the tectorial membrane was quantified using a stroboscopic computer vision imaging system and Doppler optical coherence microscopy, both of which are sensitive to nanometer displacements at audio frequencies. Freeman and his team plan to investigate the possibility that this new mechanism contributes to genetic disorders of hearing, which are known to result from mutations of the tectorial membrane. 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, Boston VA Healthcare System, Tufts University School of Medicine, University of Pittsburgh School of Medicine, Oregon Health and Sciences University, Ludwig Maximilians University, Germany, Erlangen University, Germany and the Medical University of Vienna, Austria. The group performs studies in clinical ophthalmology with investigators at the New England Eye Center, 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 (OCT) 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 there are an estimated 20 to 30 million ophthalmic OCT imaging procedures worldwide every year. OCT is also an emerging imaging modality for intravascular and endoscopic imaging.

Working in collaboration with two companies, Thorlabs and Praevium, Professor Fujimoto's group has developed optical coherence tomography (OCT) methods using on vertical cavity surface emitting lasers (VCSELs). VCSEL frequency swept laser technology for OCT enables dramatic improvements in imaging speed, imaging range and system configurability. They have recently demonstrated a multimodal ophthalmic instrument which integrates retinal imaging with anterior eye and full eye length imaging. These advances are relevant for the next generation of clinical ophthalmic OCT imaging.

Working with collaborators at the Harvard Medical School and Boston VA Healthcare System, the group is investigating endoscopic OCT for improving the diagnosis and treatment monitoring of gastrointestinal cancers. The group is also working with collaborators at the Beth Israel Deaconess Medical Center developing 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 from positive or close margins.

Professor Martha Gray heads the Madrid-MIT M+Visión Consortium and her primary focus during the last year has been on developing, implementing and documenting training approaches that promote and accelerate translational biomedical research with potential for high impact. Her emphasis lies in the M+Vision Fellowship program, 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+Vision Program has served to train both the fellows and the involved faculty. The first cohort of fellows just completed the second year of the fellowship, where each group of 10 fellows developed a portfolio of six translational projects in the biomedical imaging domain, addressing a major unmet medical need and with a high potential for impact. 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. This first team of fellows has completed about 18 months of research. They have published six abstracts in the top-ranked conferences; have numerous submitted manuscripts (the first just published); have at least 16 patent disclosures; and 4 provisional patents submitted. Considering that each of these projects represent new areas, this approach has resulted in compelling projects and comparatively rapid progress. This program and its results have the potential to influence training approaches at MIT and elsewhere. Working together with experts in innovation and in educational assessment, Professor Gray and her colleagues are in the process of accumulating objective and anecdotal data from the M+Vision fellows and faculty.

The most interesting results of the projects include:

- *Team Eye*: This team is developing an innovation to allow access to eye glass prescriptions for all. In addition to developing their innovative technology that allows for an objective, inexpensive, and easy to use device, the team has won a MISTI-India grant to travel to India to learn firsthand about the market, business, and user landscape. And, as they work towards commercialization, they have entered and performed very well in numerous business plan competitions, including most recently, Harvard's Presidential challenge, where they were runner ups.
- *Team Colo*: This team's manuscript is the first from the M+Vision projects to be out in press. M+Vision co-director, Julio Mayol, a GI surgeon in Madrid wrote, "In this outstanding paper, Vicente Parot and colleagues describe a novel technological solution (Photometric Stereo Endoscopy) for a relevant need: to decrease the incidence of missed premalignant lesions in the mucosa of the large bowel of patients undergoing colonoscopy…This is one of the most promising advances in imaging technology in the field of gastrointestinal endoscopy in decades."

Professor Jongyoon Han's Group research focuses on molecular and cell separation and sorting technologies, as well as novel use of various types of ion selective membranes. As reported in two recent publications (Hou et al., *Scientific Reports*, 3, 1259 (2013), and Guan et al., *Scientific Reports*, 3, 1475 (2013)), Professor Han and the Micro/Nanofluidic BioMEMS Group is breaking new ground for high-throughput cell separation and sorting. Taking advantage of the novel fluidic phenomena occurring in 'inertial microfluidics', solutions that contain micron-sized cells and particles can be flown in a very high flow rate (up to ~1mL/min) in a narrow microfluidic channel (~100µm) to achieve unique, size-based separation. Due to its extremely high flow throughput, this new class of microfluidic channels can be used to process large volumes of biofluids, significantly advancing the current state of the art of cellular sample processing. For example, this technique has been used to separate and enrich circulating tumor cells (CTCs) directly from cancer patients' blood, even if these cells are extremely rare (~10's of CTCs per mL of patient blood). Compared with the previous antibody-based technique, this new microfluidic system can collect more CTCs from patients due to high-throughput, in a non-invasive manner that allows downstream characterization of patients' CTC for potential functional metastatic screening in the future. This work was mainly done in Professor Han's group in the SMART Center of Singapore, and the technology is commercially licensed to a local startup company (Clearbridge Biomedics, LTD. PTE., Singapore). Clinical testing is underway in many hospitals worldwide to validate the technology.

Professor Timothy Lu's Synthetic Biology Group seeks to construct and re-encode biological systems from the ground up using synthetic biology. In the past year, the Lu group has published three 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 *E. 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 interrogate the states of these synthetic devices with fluorescent reporters and PCR. 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* and was featured on the cover, P. Siuti, J. Yazbek, and T. K. Lu, "Synthetic circuits integrating logic and memory in living cells," *Nature Biotechnology*, vol. 31, no. 5, pp. 445-452, February 10, 2013 (online).

A central goal of synthetic biology is to achieve multi-signal integration and processing in living cells for diagnostic, therapeutic, and biotechnology applications. Digital logic has been used to build small-scale circuits but other paradigms may be needed for efficient computation in the resource-limited environments of cells. Although the digital abstraction is a powerful one for electronics, it is limited by finite cellular resources and synthetic parts available for design; thus, other paradigms are needed for efficient computation in resource-limited cellular environments. The Synthetic Biology Group has shown that synthetic analog gene circuits can be engineered to execute sophisticated computational functions in living cells using just three transcription factors. Such synthetic analog gene circuits exploit feedback to implement logarithmically linear sensing, addition, ratiometric, and power-law computations. The circuits exhibit Weber's Law behavior as in natural biological systems, operating over a wide dynamic range of up to four orders of magnitude, and can be architected to have tunable transfer functions. Their circuits can be composed together to implement higher-order functions that are well-described by both intricate biochemical models and by simple mathematical functions. By exploiting analog building-block functions that are already naturally present in cells, this paradigm efficiently implements arithmetic operations and complex functions in the logarithmic domain. Such circuits may open up new applications for synthetic biology and biotechnology that require complex computations with limited parts that need wide-dynamic-range bio-sensing, or that would benefit from the fine control of gene expression. This work was done in collaboration with the Sarpeshkar Lab and was published in *Nature*: R. Danial, J. Rubens, R. Sarpeshkar, and T. K. Lu, "Synthetic Analog Computation in Living Cells," *Nature*, vol. 497, no. 7451, pp. 619-623, May 15, 2013.

Despite rapid advances over the last decade, synthetic biology lacks the predictive tools needed to enable rational design. Unlike established engineering disciplines, the engineering of synthetic gene circuits still relies heavily on experimental trial-and-error, a time-consuming and inefficient process that slows down the biological design cycle. This reliance on experimental tuning is because current modeling approaches are unable to make reliable predictions about the *in vivo* behavior of synthetic circuits. A major reason for this lack of predictability is because current models view circuits in isolation, ignoring the vast number of complex cellular processes that impinge on the dynamics of the synthetic circuit and vice versa. To address this problem, Professor Lu's team developed a modeling approach for the design of synthetic circuits in the context of cellular networks. Using the recently published whole-cell model of *Mycoplasma genitalium*, they examined the effects of the host cell on the expression of synthetic genes and the effect of these genes on the host itself. They also investigated how codon usage correlates with gene expression and find agreement with existing experimental results. Finally, they successfully implemented a synthetic Goodwin oscillator in the whole-cell model. This work lays the foundation for the integration of whole-cell models with synthetic gene circuit models. The group foresees that this approach will be critical to transforming the field of synthetic biology into a rational and predictive engineering discipline. This work was done in collaboration with the Covert lab and was published in *Chaos:* O. Purcell, B. Jain, J. Karr, M. Covert, and T. K. Lu, "Towards a whole-cell modeling approach for synthetic biology," *Chaos*, 23, 025112 (2013).

Professor Rahul Sarpeshkar heads a research group on analog circuits and biological systems and has helped pioneer synthetic analog computation in living cells. His postdoc, who also worked closely with Professor Tim Lu, has shown that log-domain analog electronic circuits can be mapped to create log-domain DNA-protein circuits in living cells (Daniel et al., *Nature*, doi:10.1038/nature12148, May 15, 2013). As pointed out in Professor Sarpeshkar's 2010 book, the mapping is possible and efficient because both bio-molecular and electronic devices obey the same thermodynamic laws. The biological circuits are founded on a positive-feedback linearizing circuit that enables four orders of magnitude of log-linear operation, and which is similar to a prior positive-feedback linearizing electronic circuit from his lab. The linearizing circuit was used to build a 'biological slide rule calculator' to add, subtract, divide, and perform square-root-like computations with just three three genetic parts in contrast with prior digital implementations, which needed 130 parts. This work was featured by *Nature's* News and Views, which highlighted the importance of analog computation in biological systems for both scalability and efficiency, a long-standing theme of his prior work (http://www.rle.mit.edu/acbs/). The results of this research have potential to impact several applications in biotechnology, energy, and medicine which require implementations with few parts and with a small metabolic load to be practical.

The research of Senior Research Scientist Dr. Mandayam Srinivasan focuses on the development and evaluation of a desktop virtual environment (VE) system with audio and haptic (touch) interfaces to help people who are blind explore and become familiar with unknown places (e.g., a train station or a shopping center) before actually visiting them. The potential application is similar to the way sighted people use MapQuest or Google Maps. The system is also intended to enhance orientation and mobility training for blind people. The audio interface provides three-dimensional (3D) spatialized sounds (like standing in the actual space) and the user is able to feel a scale model of the simulated space through the hand-held stylus of a robotic device - like a miniature white cane. This work is the continuation of a collaborative project, funded by a NEI R21 grant, between the MIT Touch Lab and The Carroll Center for the Blind (CCB), a rehabilitation and training center for blind and visually impaired persons.

During the past year technical improvements to the system continued, such as the ability to import 3D models of MIT buildings from the data provided by the MIT Department of Facilities, refine audio and force fields, and integrate handheld GPS devices. In addition, experiments with blindfolded sighted subjects on usability of attractive and repulsive force fields as well as pilot experiments with blind subjects at the CCB were conducted. The results from the experiments suggest both further technical development and experiments with human subjects to help improve the BlindAid system.

Improved non-visual methods for exploring VEs may provide a better way for blind and visually impaired persons to interact with computers in general. Specifically, the haptic methods the group is developing could have very broad application in areas that involve learning about, or communicating spatial information. Such areas might include art appreciation, exploring the Internet, or helping students to better understand graphs in a math or science class. Just as interactions through touch-sensitive screens of mobile and tablet devices are popular among sighted users today, in the future, sophisticated 3D haptic interactions with computational devices by all users, irrespective of whether they are sighted or visually impaired, could be ubiquitous. The work Dr. Srinivasan is doing in this project will help develop the generic principles in the design and implementation of such Haptic User Interfaces.

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 the acoustic analyses of prosody has implications for cognitive models of speech production and for phonological theory, as well as applications in speech recognition and synthesis.

This year has seen continued progress in the five inter-related areas relevant to speech production planning that her group is investigating in their laboratory, including:

- *Speech-accompanying gestures:* Using software developed in their lab to display and label gestures along with the words and prosody in the spoken signal from videos of college lecturers, they have discovered that speakers' successive gestures are organized into groups, sharing for example, hand shape, location or trajectory shape. This new finding, which is the first analysis of gesture sequences rather than single gestures, has important implications both for models of speech production planning and for the creation of more natural-looking onscreen avatars.
- *Acoustic landmarks:* The group has begun a new project in collaboration with Dr. John Gabrieli in MIT's Department of Brain and Cognitive Sciences, analyzing the acoustic landmarks (abrupt changes in the spectrum of the speech signal associated with vocal tract closures for consonants) in the speech of typically-developing children as well as children diagnosed with autism, specific language impairment or dyslexia. Preliminary findings suggest that children with autism may show articulatory weakening; if confirmed in additional analyses, this would be consistent with recent proposals that autism has a motor component, and would have profound implications for the development of improved treatment interventions.
- *Phonological development:* In collaboration with Dr. Helen Hanson of Union College, Shattuck-Hufnagel's team discovered that two- to three-year-old children use a non-adult-like cues for the distinction between voiced and voiceless final consonants. This research supports an emerging new model of how speakers translate abstract representations of words into context-appropriate phonetic forms. This model has the potential to resolve a long-standing mystery in speech processing (i.e. how speakers and listeners learn the systematic but fine-grained phonetic patterns that are seemingly below the threshold of perception), and thus to substantially improve the performance of automatic speech recognition systems.
- *Intonation alignment:* In collaboration with Dr. Jon Barnes of BU and Dr. Nanette Veilleux of Simmons College, this group determined that listeners' perceptions of different intonation patterns are influenced by the shape of the F0 contour and not just the location of F0 peaks and valleys. This finding has powerful implications for models of speech processing, as well as for the synthesis of more natural sounding speech.
- *Speech disfluencies as evidence for production planning models:* Recent experiments have demonstrated that tongue twisters with sentence structure and prosody (e.g. The top cop saw a cop top) elicit different types of errors than twisters with word-list structure. This finding lays to rest the claim in the literature that the articulatory intrusions elicited by word-list twisters are representative of the errors that occur in typical speech, and makes it clear that a more complex model of serial ordering in speech is required. This result also opens up a new area of investigation into the factors that incline a speaker to produce articulatory vs. cognitive errors, such as rhythmic regularity and pair-wise alternation of sounds.

In summary, this year has seen substantial steps toward the integration of the various strands of speech-production-related research into a coherent framework which is intended to support the development of a production model. Additionally, due to the arrival of Dr. Elizabeth Choi in their laboratory, they are taking similar steps toward the development of an implemented model of human speech perception as well.

Professor Collin Stultz and the Computational Biophysics Group is focused on the development of an improved understanding of disease processes at the molecular level and to use these new insights to build novel therapeutic tools. Their approach to achieving this involves both the building of computational/theoretical models and conducting biochemical experiments that are designed to test and refine these models. Stultz' research has been concentrated in three broad areas. First, the group has been concerned with understanding the relationship between localized conformational changes in collagen and collagen degradation. Since collagen degradation plays an essential role in the pathogenesis of atherosclerosis, rheumatoid arthritis, and cancer, a comprehensive understanding of this process is of enormous importance. Secondly, they have developed a deep interest in understanding the structure of intrinsically disordered proteins that play a role in neurodegenerative disorders. Lastly, they have explored different methods for identifying patients who are at risk of death post myocardial infarction.

Professor Stultz and his group have made significant progress in understanding the nature of conformational changes in collagen, at an atomistic level of detail, that promote collagen degradation (also known as collagenolysis). Their recent work also suggests that the cleavage site can adopt partially unfolded states in the fibril. More precisely, in the fibrillar state, the presence of the enzyme is needed to ensure that the unfolded cleavage site adopts states that are complementary to the active site (*Journal of Molecular Biology* 425(10): 1815-1825, 2013).

In their work on intrinsically disordered proteins, the group recently conducted studies to understand the structural preferences of alpha-synuclein – a protein that plays a pathogenic role in Parkinson's disease. Although alpha-synuclein is normally considered to be a disordered protein, recent work suggests that it can adopt an ordered tetrameric structure under in the cell; however, these results have been difficult to reproduce experimentally. Stultz' recent study used a combination of experimental observations and detailed calculations to garner insights into the structure of alpha-synculein under physiologic conditions. They conclude that the majority of the protein is disordered in the cell, but that a small fraction (~2-8%) can adopt an ordered helical tetrameric structure (*Journal of the American Chemical Society* 135: 3865-3872, 2013). These data help to reconcile seemingly contradictory experimental observations and was highlighted by the April 1, 2013 MIT News.

The Computational Biophysics Group also has conducted computational studies on abeta – a protein that plays an important role in Alzheimer's disease. Their study helped to explain why some variants of abeta are more apt to form aggregates *in vitro*. These observations are important because aggregates of abeta are believed to the pathogenic agent in Alzheimer's disease (*Biophysical Journal* 104: 1546-1555, 2013).

Lastly, Professor Stultz and his team have continued their work on using electrocardiographic data to identify patients at high risk of adverse cardiovascular events. They recently obtained several patents on their algorithms and one of these patents has been licensed to startup company in the Cambridge area (Quanttus).

The Computational Physiology and Clinical Inference Group, co-directed by Professor George Verghese and Principal Research Scientist Dr. Thomas Heldt, is focused on "bedside informatics," using physiologically based dynamic models to make sense – on the seconds to minutes to hours timescale – of multivariate monitoring data collected at bedside in critical care or the emergency room or operating room, extending to the general wards and even ambulatory situations. Several clinical collaborators participate in their work.

During the past year, the group extended its work on noninvasive estimation of intracranial pressure (ICP) by initiating its own data collection effort with collaborators at Beth Israel Deaconess Medical Center, to overcome the limitations of the archived data used in its earlier validation studies. Preliminary results show distinct improvements in the accuracy and precision of their method. Collaborations on further data collection and validation, using hydrocephalus and traumatic brain injury patients, are underway with Boston Children's Hospital and Boston Medical Center. The group's approach to noninvasive ICP estimation was awarded a US patent in February 2013.

Another major research thrust in the group focuses on classification of disease state based on capnography, which records CO2 concentration as a function of time in exhaled breath. Results recently submitted for publication demonstrate the excellent ability of appropriately processed capnograms to screen for patients with chronic obstructive pulmonary disease (COPD) relative to normal subjects, on the basis of data collected over a few minutes of normal breathing. Similarly, a capnography-based diagnostic test distinguishes COPD patients from those with congestive heart failure (CHF) with good accuracy. A patent application related to this approach has been filed.

Further work in the group focuses on early detection of impending decompensation in pediatric patients on the general wards and on analyzing electrocardiograms for signatures of brain injury in neurocritical care patients.

With Dr. Heldt's recent appointment as Assistant Professor of Electrical and Biomedical Engineering in MIT's EECS Department, and as Helmholtz Career Development Professor in MIT's new Institute for Medical Engineering and Science, the group's research agenda is expected to both consolidate and broaden.

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 to applied neuroengineering. Professor Voldman and the Biological Microtechnology and BioMEMS Group have been working on two areas this past year: 1) developing microsystems for manipulating cells for basic and applied cell biology, and 2) microsystems for human health. The first area includes devices for studying immune cells, neurons, and stem cells, while in the second area involves work on point-of-care diagnostics and neural probes.

In terms of microfluidics for studying cell biology, Professor Voldman and his group demonstrated for the first time that AC electric fields could be used to control axonal growth in a non-contact format (*Lab on a Chip*, 2013). This is exciting because controlling axons is important for everything from basic neurobiology to repairing nerve lesions, but current methods to direct axonal growth have significant limitations. The group hypothesized that the electrokinetic forces could steer axons, and indeed they have found this to be the case, allowing electrically controlled and thus dynamic steering of axons. Their work on microsystems for human health is more preliminary, but they have entered into a project with Maxim Integrated, a microelectronics company, to develop a highly multiplexed all-electronic biosensor that can measure a large number of proteins from a drop of blood, eventually removing the need to have blood work done at central labs. The team's devices for fundamental cell biology have applicability to a wide range of biological investigation; for example, they have developed devices to study communication between immune cells, and these are useful for studying communication between cancer cells, stem cells, etc. The impact of their research is significant.

Following 24 years of work in the development of a retinal implant for the blind, John Wyatt's Retinal Implant Research Group has decided to push hard toward a commercially viable device. They have focused on the development of a high-density, miniature implantable wireless neurostimulator, capable of driving over 256 separate microelectrodes. Over the last year, Professor Wyatt's group has further developed the microchip that supplies power and data to the implant. Once they have succeeded in successfully implanting their device in a half-dozen patients, the consequences will be significant for the millions of people world-wide who have lost vision due to outer-retinal degenerations like retinitis pigmentosa and macular degeneration. Furthermore, the technology they are developing will make it possible to implant stimulators that drive hundreds of microelectrodes rather than the tiny numbers (certainly under a dozen) implantable devices now use, which will allow a great improvement in the electronic stimulation and control of the body when medically required.

Professor Mehmet Fatih Yanik's lab, The 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, ultrafast optics, advanced microscopy, quantum physics, genetics, and biochemistry. The group also works with a variety of organisms and preparations ranging from *C. elegans*, zebrafish, 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.

Professor Yanik and his team have had an impactful year with their research:

- The group demonstrated hyper-dimensional in vivo high-throughput screening concept that allows them to rapidly identify mechanisms of action of unknown chemicals in vivo. The first part of their study was published in *Nature Communications* this year.
- They demonstrated reprogramming of skin cells to induced pluripotent stem cells from patients whose cells were previously completely resistant to reprogramming.
- The group developed a technique to differentiate and generate dopamine neurons lost in Parkinson's disease using non-integrating reprogramming technology. They are now trying to make these neurons at highest purity compatible with human implantation.
- They demonstrated 3D laser micro-patterning of complex vasculature and protein cues that can control guidance and homing of cells in 3 dimensionally defined locations inside tissue. A manuscript is under preparation.
- The team developed a technology that allows them to rapidly generate genetically engineered *C. elegans*. They are currently generating large genetically engineered animal libraries in preparation for a paper.
- Lastly, Yanik and his group just finished developing a robotic technology that allows them to automatically sample single neurons from brain tissue cultures for genomic analysis.

Nanoscale Science and Engineering

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

Professor Karl Berggren researches methods of nanofabrication, especially applied to superconductive quantum circuits, photodetectors, high-speed superconductive electronics, and energy systems. His group demonstrated, for the first time, the use of an aberration-corrected scanning transmission electron microscope - in collaboration with Brookhaven National Lab - for the fabrication of 2 nm features, equivalent to 10 atoms across. These are the smallest structures ever achieved by direct exposure of resist by using a scanning electron beam. Electron-beam lithography (EBL) at the sub-10 nm scale will facilitate the fabrication of functional devices previously considered as merely conceptual, such as nano-optical chips with individually addressed quantum dots (QDs), high quality-factor plasmonic nano-antennas, and single-molecule circuits. For example, within the scope of sub-10 nm lithography, Professor Berggren's group has also developed a lithographic process for the placement of individual colloidal QDs, a long standing challenge to the integration of colloidal QDs into functional devices. Professor Berggren, in collaboration with the Bawendi research group in the Chemistry Department, has developed a technique to control the placement of 5 nm diameter QDs at predetermined positions by EBL. Photoluminescence measurements have shown that the precisely placed QDs are optically active after the fabrication process.

Professor Dirk Englund joined the MIT Electrical Engineering and Computer Science Department faculty in January 2013 as assistant professor. He leads the Quantum Photonics Laboratory and his research focuses on quantum technologies based on semiconductor and optical systems, with the goal of controlling quantum states in photons and semiconductor spin systems to address problems in communication, computation, and metrology. His major research accomplishments include the control of light-matter interactions of single quantum states in quantum dots and diamond nitrogen vacancy centers, high-brightness single photon sources, group III/V photonic crystal lasers, and integrated photonic networks for quantum information processing.

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? Can they 'See, Hear, Sense and Communicate'? 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 towards 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. The research highlights of the past year involve harnessing the inherent scalability of fiber production and an in-fiber Plateau–Rayleigh capillary instability for the fabrication of uniformly sized, structured spherical particles spanning an exceptionally wide range of sizes from 2mm down to 20 nm (Kaufman, J.J., et al., "Structured spheres generated by an in-fibre fluid instability," *Nature*, 487, 463-467, July 2012). Additionally, the group has been working with large-active-area piezoelectric fibers which can be woven into extended and flexible ultrasound transducing fabrics. This work published in *Advanced Materials* (Chocat, N., et al., "Piezoelectric Fibers for Conformal Acoustics," *Advanced Materials* 24, No. 39, 5327-5332, October 2012) opens significant opportunities for large-area, flexible and adjustable acoustic emission and sensing for a variety of emerging applications. Another significant development was the team's demonstration of a high-throughput method for synthesizing zinc selenide (ZnSe) in situ during fiber drawing. The ability to synthesize new compounds during fiber drawing at nanometer scale precision and to characterize them at the atomic-level extends the architecture and materials selection compatible with multimaterial fiber drawing, thus paving the way toward more complex and sophisticated functionality (Hou, C., et al., "Direct Atomic-Level Observation and Chemical Analysis of ZnSe synthesized by in situ high-throughput reactive fiber drawing," *Nano Letters*, Vol. 13, No. 3, 975-979, March 13, 2013).

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. This includes:

- The optimization of graphene synthesis and fabrication steps for high performance transistor devices, the synthesis of hybrid graphene-hBN structures
- Using graphene as transparent electrodes for organic photovoltaic (OPV) solar cells
- Synthesis of AB-stacked bilayer graphene
- Fabrication of aerogel materials from 1D nanowires and 2D nanosheets
- Synthesis of other two-dimensional materials: including MoS2, MoSe2, WS2 and WSe2

During the last year, great strides were made by the group. By using their CVD grown hBN as a substrate, they found their CVD graphene devices showed higher mobility - up to 10,000 cm2/Vsec compared to previous results with CVD graphene on SiO2/Si substrate of mobility values 3000-5000 cm2/Vsec. This is a big improvement for graphene devices, and currently they are trying to improve the hBN synthesis to obtain more uniform layers. For the graphene as transparent electrode application, they successfully fabricated highly efficient polymer based photovoltaic solar cell on flexible substrate with graphene electrodes. The power conversion efficiency is up to 5%. In addition, they have been developing various applications for the aerogel materials made from 1D nanowires and 2D nanosheets, and they recently found unique advantages for water and air treatment. They are writing a manuscript and filing a patent at the same time. Lastly, they have successfully developed the CVD synthesis of large area (mm2 to cm2) MoS2 on insulating substrates. The methods have also been extended to growth of WS2, MoSe2 and WSe2. One manuscript was published in *Nano Letters* and one patent has been file. Currently, they are working on two other manuscripts on this topic and an additional patent.

Their method for interface engineering has helped move forward the real application of graphene transparent electrode, not only in photovoltaic devices, but also LED devices, and touch screen. And, their work on aerogel material preparation has various applications including unique advantages for water and air filtering. In addition to the super capacitor applications, they also started to investigate the Li-air battery applications and have interesting preliminary results.

This year, Professor Henry I. Smith and his group in the Nanostructures Laboratory focused on developing techniques for fabricating 3-dimensional photonic-crystal structures by stacking pre-patterned silicon membranes with thicknesses of about 200 nm. The Si membranes were all patterned with a 2-dimensional array of 200 nm-diameter holes on a 600 nm pitch. When properly aligned in X and Y, and stacked on top of one another a 3D photonic crystal structure is formed.

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 devices.

Vladimir Bulović leads the Organic and Nanostructured Electronics Laboratory, directs the MIT Microsystems Technology Laboratories and co-directs the MIT-ENI Solar Frontiers Center. Professor Bulović's research interests include studies of physical properties of organic and organic/inorganic nanocrystal composite thin films and structures, and development of novel nanostructured optoelectronic devices.

Coherent exciton interactions in organic materials are responsible for a number of optical phenomena including exciton-polariton condensation, anomalous second order phase transitions, and more recently photon Bose-Einstein condensation. However, until now, exciton coherence has not been harnessed to control and improve organic optoelectronic device performance. In their latest work on superradiant lasing from organic dye microcavities, Professor Bulović and his colleagues demonstrate that cooperative interaction between excitons in a microcavity containing a solid-state organic gain layer leads to superradiant emission, manifested as a 10-fold reduction in lasing threshold, resulting in a record low threshold for an organic microcavity of 400 nJ/cm^2. While great emphasis has been placed on polariton lasers as a route to low-threshold coherent emission, their system shows that coherent interactions between excitons, rather than strong coupling with the photon field, is a route towards low-threshold lasing.

Professor Peter Hagelstein's overall research efforts have included the invention of semiconductor technology that could allow efficient, affordable production of electricity from a variety of energy sources, as well as continuing investigations of low-energy nuclear reactions. Over the past year, Professor Hagelstein and his Energy Production and Conversion Group's research focused on cold fusion; they are studying anomalies from a fundamental physics perspective. While their research is primarily theoretical, they have the opportunity to collaborate with many experimental teams, as well as other theorists. About two and a half years ago, the team proposed a new fundamental Hamiltonian for describing anomalies in cold fusion related experiments. Since the beginning, models based on this Hamiltonian have shown effects similar to those seen in experiments, but quantitative agreement has proven elusive. Quite recently, a new analysis of the model has yielded constraints that appear to be consistent quantitatively with collimated x-ray emission in the Karabut experiment. This work was presented at an international conference in July. Additionally, Professor Hagelstein and his group are collaborating with a group at SRI to develop a new experiment intended to demonstrate the conversion of vibrational energy to nuclear excitation in Hg-201, with a transition energy of 1565 eV. This experiment might be considered to be a controlled version of Karabut's experiment which in their view demonstrates the effect.

Principal Research Scientist Dr. Kyung-Han Hong works together with Professor Franz Kaertner in the Optics and Quantum Electronics group. Dr. Hong's accomplishments span a range of topics in ultrafast laser science. His research has focused primarily on the ultrashort pulse amplification and its application to high-field physics such as HHG and relativistic optics. He is also active in a wide range of ultrafast optics research topics such as ultrashort pulse generation and measurement techniques. Dr. Hong has been focused on two main projects this year. The first involves the development of a high-flux soft X-ray high-harmonic generation (HHG) source. As a driving source of HHG, Dr. Hong and his colleagues nearly completed a femtosecond high-power mid-infrared laser source, generating multi-mJ of energy at a kHz repetition rate, for the first time. This source is expected to generate coherent soft X-rays with a flux of ~108 photon/s in the water-window range (2-4 nm) via HHG and serve attosecond science experiments in the soft X-ray range. They also studied and uncovered the fundamental features of HHG, such as high-harmonic spectroscopy under macroscopic effects, the quantum mechanical calculation of recombination amplitude, and the effect of complex ionization time on efficiency scaling. His second project has been to develop a compact terahertz (THz)-based electron accelerator. Towards the end goal of "CUBIX (compact ultrafast bright and intense X-ray)" source, funded by DARPA AXiS program, they are implementing a THz accelerator that can substitute a conventional linear accelerator (LINAC). They demonstrated a powerful THz source driven by an ultrafast high-power laser and succeeded in demonstrating a record-high conversion efficiency from infrared to THz. The THz accelerator has been designed and built up since early 2013.

Professor Qing Hu studies terahertz quantum cascade lasers and electronics; sensing and real time THz (T-rays) imaging using quantum cascade lasers and focal-plane cameras. His group has achieved many world records in terms of performance of their THz quantum cascade lasers including but not limited to: highest operating temperature in the pulsed mode ~200 K without field and 225 K with magnetic field), highest operating temperature in the CW mode (117 K), and highest power levels of ~250mW. They have performed real-time Thz imaging at a video rate of ~20 frames/second; have developed a novel tuning mechanism that is qualitatively different from all the other tunable lasers; and have achieved continuous tuning over a broad frequency range (~330 GHz). These are experiments with the potential to lead to significant improvements in sensing, imaging and high bandwidth communications.

The overall focus of Professor Erich Ippen's research is on femtosecond optics and its applications to science and technology. His group has continued development of compact optical fiber and waveguide lasers for use in optical clocks and signal processing. Femtosecond studies of the materials and components involved are also central to their research. Professor Ippen's group has been at the forefront of developing higher (GHz) repetition rate fiber lasers for optical combs and ultrafast sampling. This past year they investigated detailed femtosecond pulse characteristics under a variety of operating conditions in several GHz fiber laser designs mode-locked with custom-designed semiconductor saturable absorber mirrors fabricated by Professor Leslie Kolodziejski's group. These studies yielded demonstrations of timing jitter at 1 GHz of less than 5fs. Such low jitter could be used to dramatically increase the precision of high-speed sampling and high-resolution analog-to-digital conversion. Professor Ippen's group extended their studies of TiO2 nanostructures which are of interest for 1.5 μm wavelength nanophotonics because of their compatibility with silicon processing and their immunity to two-photon absorption in that wavelength range. Direct characterization of the ultrafast nonlinear index of refraction was achieved via a perturbational heterodyne femtosecond pump-probe method in addition to observations of high-power spectral broadening and Raman shifting.

Their work on optical combs is synergistic with research in the Center for Ultracold Atoms 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 Franz Kaertner, is motivated also by signal processing demands of LIDAR and RADAR applications and by the timing precision required by Free Electron Laser (FEL) facilities. Professor Ippen's studies and demonstrations of silicon nanophotonic circuits, also in collaboration with Professor Kaertner, are of general importance to the advance on on-chip photonic communication and control and are synergistic as well with the research of Professor Michael Watts.

Professors John Joannopoulos and Marin Soljacic work together as a team in the area of nanophotonics. They are enthusiastic about the novel photonic state they discovered recently. In order to build almost any optical device (e.g. laser, optical fiber, even LED or solar-cell) one needs to have a way of trapping (confining) light. Most commonly, this is accomplished with metallic reflectors, similar to common mirrors, or total internal reflection, like in an optical fiber. There are other, more exotic ways to do this (e.g. photonic crystals, Anderson localization); however, all of the previously known methods of trapping light explore the fact that the outgoing medium is chosen such that does not have and support suitable modes of light to which the incoming modes of light could couple to. Once the incoming modes encounter such a medium, they do not have a choice: they cannot propagate into such a medium and are thereby trapped - or reflected. Professors Joannopoulos and Soljacic have demonstrated a new way of trapping light. Light in their structures is trapped, although there do exist modes to which this light is allowed to couple to. Instead, their light is trapped due to a subtle interference phenomenon, where light destructively interferes with its own outgoing radiation. This phenomenon happens at one exact frequency; light of surrounding frequencies is not trapped. Mathematicians refer to this as an "embedded eigenvalue." There is high theoretical interest in embedded eigenvalues (dating at least to von Neumann and Wigner (late 1920s)), but there are no experimental demonstrations of symmetry unprotected embedded eigenvalues so far. This finding is published in *Nature* (Hsu, C-W., et al, Vol.499, p.188, (2013).). These results might enable general new classes of large-area low-threshold lasers, as well as chemical sensing systems, synergistic with the research of Professor Watts.

In the last year, Professor Steven Johnson's research has primarily focused on problems in nanophotonics (electromagnetic phenomena in wavelength-scale media), but he has also worked on nanofluidic and micromechanical phenomena. In computational photonics, his group has demonstrated several new "inverse-design" techniques for large-scale optimization-based discovery of photonic devices, including counter-intuitive taper couplers to "slow-light" waveguides that are resistant to manufacturing imperfections ("robust" optimization), coated spherical particles with maximal broadband scattering efficiency (for "smoke grenade" obscurance applications), and new multimode optical devices (bends and mode squeezers that transport all modes without scattering or delay differential) that were demonstrated experimentally in collaboration with Professor Lipson at Cornell. Johnson's group has also studied electromagnetic phenomena arising from quantum or thermal fluctuations, such as Casimir forces and near-field heat transfer, and have obtained several important results: a new surface-current formulation that exploits "boundary-element" computational tools for near-field heat transfer; theoretical discovery of the first non-monotonic anomalous near-field heat transfer induced by geometry; and the first experimental observation of Casimir forces in integrated MEMS devices (in collaboration with H.–B. Chan of Hong Kong University of Science and Tech.).

Professor Franz Kaertner and his group focus on highly efficient Thz generation; 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 the calibration of astrophysical spectrographs (in collaboration with Smithsonian Center for Astrophyisics at Harvard).

Professor Kaertner and his team have made significant research progress during the last year. They demonstrated the highest optical to Thz conversion efficiency of almost 4% using mJ-pulses from a regenerative amplifier with tilted pulse fronts focused into cryogenically cooled Lithium-Niobate. They believe that they can scale this generation mechanism to 10% efficiency. This is important because it allows for efficient Thz sources and its use for particle acceleration. Thz pulses are optimum for the construction of hard x-ray sources for a variety of applications. Additionally, a novel cryogenically cooled composite thin disk laser with a strict relay imaging cavity has been designed and constructed. This will enable the development of multi-Joule pulse sources operating with multi-kW average output power. Such lasers are important for advanced materials processes, pumping of optical parametric chirped pulse amplifiers and attosecond science. In a first step, the team demonstrated > 100 mJ pulses at 100 Hz repetition rate, i.e. an average power of 10W demonstrating the concept. They will increase both pulse energy and average power over the next years. Lastly, they have designed a set of components enabling a Thz driven electron accelerator. The components are currently under testing and will enable compact relativistic electron beams for advanced X-ray sources.

There are important long-range applications of their research. Both the high energy and high average power laser technology as well as the efficient Thz generation and Thz accelerator will be the basis for advanced x-ray sources eventually for EUV – lithography, phase contrast imaging and materials processing like laser shot peening. They are currently pursuing this technology within the DARPA CUIBX Program, which is executed jointly with Professor Karl Berggren, Luis Velasquez-Garcia, William Graves and T. Y. Fan from Lincoln Laboratory.

Professor Leslie Kolodziejski and Principal Research Scientist Gale Petrich investigate the fabrication of optoelectronic devices in III-V compound semiconductors and on materials issues related to Si 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 Si-based photonic integrated circuits. The most significant results were the installation of an ion-assisted sputtering system and the use of that system to achieve low optical loss aluminum oxide films on 150mm and potentially 200mm wafers.

As for future applications, the development of rare-earth doped oxides for Si-based photonic integrated circuits provides the optical amplification that is necessary to overcome the loss that is associated with routing the 1550nm based wavelength division multiplexed optical signals within the photonic integrated circuit. By providing optical amplification to Si-based photonics, the integration of Si-based photonic devices with CMOS based electronics is possible.

Professor Michael Watts and his Photonic Microsystems Group has been focused on 3D integration of silicon photonics with CMOS electronics and on-chip lasers for a variety of applications, including ultralow power wavelength division multiplexed (WDM) optical communications, optical phased arrays, optical beam-steering, low phase noise optical-microwave oscillators and microwave signal generation. Professor Watts' group has demonstrated the largest optical phased array ever produced, at 4096 elements, projecting the MIT-logo in the far-field; this was published in *Nature* in January 2013. Additionally, Professor Watts and this team demonstrated the ability to steer such a nanophotonic phased array using thermo-optic phase shifters. Additionally, they demonstrated Erbium doped aluminum oxide based lasers on a silicon platform; a technology that Professor Watts expects will fold into the rest of their silicon photonics platform. The group also demonstrated a new record in low power silicon modulators, achieving 1fJ/bit in modulators running at 25Gb/s in the world's first 300mm silicon photonics platform this platform was developed by Professor Watts' research group in collaboration with CNSE Albany. Finally, Professor Watts is close to demonstrating the most intricate 3D CMOS-photonic chips ever produced. The results from the phased arrays, low power communication links, and microwave-photonic circuits are likely to impact accident avoidance technologies in automobiles with chip-scale LADAR. The low power communication links are likely to impact the implementation of low power, high-performance data center, and their work on optical-microwave oscillators is likely to impact wireless communications and Global Positioning Systems.

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.

The Quantum Engineering Group 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, Professor Paola Cappellaro and her group follow two directions: a bottom-up approach based on single electronic spins in diamond, and a top-down approach of studying large nuclear spin systems with solid-state NMR techniques.

In the first approach, the group is studying a diamond defect, the Nitrogen-Vacancy (NV) color centers, that can be used as building blocks for quantum computation and as sensors for magnetic fields and rotations (magnetometers and gyroscopes). The focus of the past year has been on studying novel strategies to measure the time-dependent profile of magnetic fields with this quantum probe. (This work is supported by NIST, DARPA QuASAR and ARO MURI QuISM awards).

Professor Cappellaro's group developed a strategy that simultaneously protects the quantum probe from decoherence and efficiently encodes the information about the field's time evolution. The method was successfully implemented using a single NV center in diamond; specifically, they reconstructed the simulated time-profile of a neuron's action potential. Future experiments on real neurons are planned with the contribution of collaborators. The group further extended the method by a careful theoretical analysis that lead to an improvement of the initial strategy, based on the Walsh transform, to include compressive sensing techniques. This will lead to substantial savings on the experimental time, thus making the time-profile reconstruction technique a useful tool for many problems, from neuronal activities to protein structure reconstruction. A second research direction was toward the precise control of nuclear spins associated with the NV center, which can be used as memory, to improve the readout of the electronic spin and for small quantum algorithms. (This work is supported by AFOSR YIP.) In particular, Professor Cappellaro's group experimentally studied the control of the nitrogen nuclear spin associated with the NV center and its coherence properties which are mainly determined by the electronic spin dynamics. In addition, the group investigated time-optimal control methods to indirectly manipulate the nuclear spin via the manipulation of the electronic spin. While the group plans to experimentally apply these strategies to the NV center system, the methods are much more general and will be applicable to both quantum and classical systems, to robotic systems in particular.

The second approach was to study large quantum systems, comprising many nuclear spins via Nuclear Magnetic Resonance (NMR), in order to explore coherence properties, control, and noise reduction techniques. In the past year, this group has investigated the spin systems in crystals of Fluorapatite (FAp). This system is of particular interest since it presents a quasi-one-dimensional geometry that is amenable to the study of quantum information transport and quantum simulation. They theoretically and experimentally studied the decoherence properties of correlated spin states in linear chains. (This work is supported by MISTI, the Hayashi Seed Fund, and a NSF-DMR award.) Because of the one-dimensional character of the spin system studied, Professor Cappellaro's group was able to gain a deeper insight into the decay of highly correlated spin states. These states, which possess properties akin to entangled states, are critical for the experimental implementation of quantum information algorithms, but they are more fragile to external influences and decoherence. Thus, it is crucial to characterize their decay in order to develop strategies for their preservation. In the future, the group plans to further explore noise-cancellation strategies for this type of correlated states.

Professor Isaac Chuang's group is studying theoretical and experimental quantum information science, and in the past year his team has developed and demonstrated a novel superconducting surface-electrode ion trap system for quantum computation. His group has also collaborated with the University of Innsbruck on a joint project demonstrating a scalable implementation of Shor's quantum factoring algorithm, using trapped ion technology. The future of quantum computation is highly dependent on finding new applications, and towards this end, Chuang's group is working on formulating new quantum algorithms for machine learning, including accelerated sampling from Bayes' network distributions.

Professor Seth Lloyd's research is on the interplay between information and energy in physical systems, concentrating on the role of quantum coherence and decoherence. He studies quantum computation, quantum communication, and nanoscale energy transport. During this time period, Professor Lloyd and his colleagues obtained novel results in secure communications, quantum algorithms for the analysis of big data, and quantum energy transport in naturally occurring and artificial systems.

As part of a DARPA-funded program on secure communications (Quiness), Professor Lloyd and colleagues Dirk Englund, Saikat Guha (BBN), Cosmo Lupo, Jeffrey Shapiro, Mark Wilde and Franco Wong devised a novel method for secure communication - the quantum enigma machine. The classical enigma machine is a device that scrambles up a message using a predetermined small shared secret key. The hope was that the message could not be unscrambled without the key, a hope that was famously shown to be false during WWII. The quantum enigma machine works in the same way, but using quantum states. Here, the theory of quantum data locking shows that quantum enigma machines are provably secure: in the absence of the short key, the eavesdropper obtains a vanishingly small amount of information.
This collaboration has derived the fundamental theory of `enigmatic' communication over noisy and lossy quantum channels and has devised experimental methods for constructing quantum enigma machines.

In the field of quantum energy transport, supported by DARPA and by Eni under the MIT Energy Initiative, Professor Lloyd and collaborators Angela Belcher and her group, together with Masoud Mohseni and Patrick Rebentrost, have performed fundamental investigations into excitonic transport in virus-templated systems. Professor Belcher and her group have the capacity to design the binding sites on the exterior of a viral phage to bind different types and densities of organic dyes and chromophores. Over an extended period of designing, testing, and redesigning, the Belcher and Lloyd groups have constructed systems that give excitonic transport of tens to hundreds of nanometers. Professor Lloyd's group has supplied theoretical expertise to analyze the quantum mechanics of the energy transport, together with data analysis and design principles for optimizing quantum transport.

In a related project, Professor Lloyd and his group have collaborated with Moungi Bawendi and Dorthe Eisele to investigate quantum energy transport in double-walled J-aggregate nanotubes. These systems exhibit strong signatures of quantum coherence and have the potential to give very long excitonic diffusion rates. In addition to participating in experiment design and data analysis, Professor Lloyd has applied his theory of optimal quantum transport to derive the tradeoffs between coherence and decoherence, order and disorder, to determine the optimal parameters for long-range energy transport.

Together with Patrick Rebentrost and Masoud Mohseni, Professor Lloyd devised a novel series of quantum algorithms for the analysis of large data sets (`big quantum data'). The simple intuition is that big data frequently is encoded as large arrays of high-dimensional vectors. Such arrays can be readily mapped to a quantum state containing exponentially fewer quantum bits – N classical bits are mapped to log N quantum bits. The resulting quantum state can then be processed using linear quantum algorithms to reveal features of the data, such as principal components, clusters, and optimal hyperplanes for dividing data clusters. Big quantum data techniques have the potential for performing highly complex data analysis using algorithms that take exponentially fewer resources than their classical counterparts. Moreover, quantum machine algorithms provide a strong guarantee of privacy: because only log N bits of the larger database are accessed, the analyzer of the database can identify global features of the data while only accessing a vanishingly small fraction of the information contained in the database.

Professor Terry Orlando directs a multi-university, multi-disciplinary research effort that is focused on using superconducting circuits for quantum computation and has additional interest in the study of non-linear dynamical systems in the crossover regime from classical to quantum behavior. During the past year, research conducted by Professor Orlando and research scientist Dr. Simon Gustavsson has proceeded along two thrusts: they continued to advance quantum control and decoherence mitigation in advanced flux qubits; at the same time, their research began a transition to investigating superconducting transmon qubits and quantum microwave resonators. The transition has required installating new cryogenic electronics, designing and simulating electromagnetic properties of the qubits and resonators, and fabricating and measuring two- and three-dimensional electromagnetic cavities in the quantum regime. This research is in collaboration with Dr. William D. Oliver and his team at MIT Lincoln Laboratory.

In addition, Professor Orlando and Dr. Gustavsson investigated the dynamics of non-linear microwave resonators in a collaboration with Professor Jonas Bylander and his group at Chalmers University of Technology in Gothenburg, Sweden. The non-linearities 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.

Their research has lead to the publication of three scientific articles on superconducting qubits in *Physical Review Letters* during the last year. One article describes their experimental demonstration using dynamical decoupling pulse sequences to improve coherence times in coupled superconducting quantum systems. Another explains and demonstrates how a superconducting qubit can be used to simulate effects of time-reversal symmetry in electron transport in mesoscopic systems. In the third article, they demonstrate remarkably improved single-qubit gate fidelities, enabled by using the qubit itself as a sensitive tool for calibrating away pulse imperfections.

There has been tremendous improvement in coherence times and the achievable gate fidelities of superconducting qubits over the last few years, in this lab and in others around the world. These systems are reaching a level of perfection where 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. Their group's signature achievement this year was the experimental demonstration of a quantum communication protocol that is immune to passive eavesdropping, i.e., one that permits Alice and Bob to communicate in complete secrecy despite the presence of an eavesdropper who is able to listen to the optical signals propagating between them. This protocol, whose theoretical description was published by Professor Shapiro in a 2009 *Physical Review A* article, is made more remarkable by the fact that it relies on entanglement, even though the communication channel's noise destroys that entanglement. As the group's 2013 *Physical Review Letter* reports, this experiment is the first to demonstrate that entanglement's benefit can survive an entanglement-breaking channel. Consequently, the group's achievement has been highlighted in *Nature* and *Physics Toda*y, and been the subject of a *Physics Viewpoin*t from the American Physical Society. In other activities occurring during the past year, Professor Shapiro, together with Dr. Baris Erkmen from the Jet Propulsion Laboratory, and Professor Keith Schwab from the California Institute of Technology, led the study program "Quantum Communication, Sensing, and Measurement in Space" for the Keck Institute for Space Studies, in which Dr. Wong headed the panel on nonclassical light sources. Professor Shapiro also chaired the organizing committee for the Office of Naval Research Workshop on Quantum Communication, in which both he and Dr. Wong made presentations.

Personnel

Professor Dirk Englund joined the MIT EECS Department faculty in January 2013 as Assistant Professor and moved his laboratory from Columbia University to RLE's Building 36. Professor Englund's research focuses on quantum technologies based on semiconductor and optical systems, with the goal of controlling quantum states in photons and semiconductor spin systems to address problems in communication, computation, and metrology.

Marc Baldo was promoted to full professor of electrical engineering.

Mehmet Fatih Yanik was granted tenure.

Martin Zwierlein was promoted to full professor of physics.

Dr. Thomas Heldt and Dr. Kyung-Han Hong were promoted to principal research scientist.

Orit Shamir (project manager), Rachel Smederovac (human resources coordinator) and Victoria Moore (fiscal officer) joined RLE headquarters.

Catherine Bourgeois was promoted to center administrator.

Susanne Patterson (fiscal officer) was honored with the 2013 MIT Infinite Mile Award.

Faculty Honors and Awards

Professor Polina Anikeeva's neural engineering efforts were recognized by the NSF CAREER award and DARPA Young Faculty Award.

Professor Vladimir Bulovic was appointed the Fariborz Maseeh Professorship in Emerging Technology. In his announcement, EECS Department Head Anantha Chandrakasan praised Bulovic with his "stellar research and technical accomplishments and his leadership in microsystems and nanotechnology."

The 2013 IEEE Donald O. Pederson Award in Solid-State Circuits was awarded to Professor Anantha Chandrakasan. The IEEE praised Chandrakasan for his "outstanding contributions to the field of semiconductor circuits in terms of benefitting society, enhancing technology and demonstrating professional leadership."

Professor Dirk Englund was appointed as the Jamieson Career Development Professor.

Professor of electrical engineering Dennis Freeman was appointed as MIT's dean for undergraduate education.

Professor James Fujimoto was awarded the SPIE Britton Chance Biomedical Optics Award in recognition of his "pioneering research in optical coherence tomography and its development as a clinical tool."

Dr. Fujimoto was also a co-recipient of the Champalimaud Vision Research Award along with other co-inventors of OCT, Mr. Eric Swanson of MIT, Dr. Carmen Puliafito, Dean of the Keck School of Medicine at U. Southern California, Dr. Joel Schuman, Chairman of Ophthalmology at the University of Pittsburgh School of Medicine and Dr. David Huang, of the Casey Eye Institute and Oregon Health and Sciences University. The Champalimaud Vision Research Award is considered one of the most prestigious awards in the field of vision research.

3dim, founded by a team of MIT engineers, earned the grand prize at this year's MIT $100K Entrepreneurship Competition. Technology from Professor Vivek Goyal's group is at the core of 3dim's nascent effort to bring 3D sensing to smart phones, tablets, and wearable computers.

The Institute of Electrical and Electronic Engineers (IEEE) Photonics Society's 2012 William Streifer Scientific Achievement Award was presented to Professor Qing Hu for his "pioneering contribution in the development of high-temperature, high-power, and broadly tunable THz QCLs, and applications in imaging and sensing."

Professor Steven Leeb received the Bose award from the School of Engineering.

Acknowledged for his "seminal contributions to the theories of quantum communication, metrology, computation, and control," Professor Seth Lloyd was presented with the Quantum Communication Award for Theoretical Research at the Eleventh International Conference on Quantum Communication, Measurement, and Computing.

Professor Tim Lu was the recipient of the 2013 Office of Naval Research (ONR) Young Investigator Award for his research on 'biologically inspired engineering of underwater adhesives with synthetic biology.'

Professor David Perreault was elected as an IEEE Fellow his extraordinary contributions "to design and application of very high frequency power electronic converters".

Professor Jacob White's "seminal work on fast integral equation solvers for integrated circuit parasitic extraction" was commended at the 50th Design Automation Conference; he was awarded the ACM/IEEE A. Richard Newton Technical Impact Award in Electronic Design Automation.

Professor Gregory Wornell, a prominent leader in the fields of signal processing and information theory, was appointed as the Sumitomo Electric Industries Professorship of Engineering.

Student Awards

Doctoral students Gabrielle Merchant and Thomas Gurry were awarded the 2013 Helen Carr Peake research assistantships, and doctoral student Audrey Fan was the recipient of the 2013 Helen Carr Peake Prize. All of the students won Peake recognition as a result of outstanding research projects seeking to improve technology used in the diagnosis and treatment of human health problems.

The 2013 Claude E. Shannon research assistantships were awarded to Mina Karzand and Kuang Xu, both doctoral students in the Department of Electrical Engineering and Computer Science. These awards support students doing research in communication.

Research and Administrative Initiatives and Events

In October, the first RLE Fair took place, aimed at encouraging community building, increasing research group interconnectivity towards furthering our mission of nurturing a stimulating environment for innovative research. The Fair was designed to provide a holistic, lab-wide experience, and showcased administrative services as well as the various research themes to demonstrate our strengths in both areas. The fair was attended by over 500 individuals, including RLE Principal Investigators, postdoctoral associates, students, and staff, as well as other members of the MIT community. Over 60 group posters were presented during the Fair, which also featured photographs from RLE's rich past.

The RLE Fair was also the stage for the presentation of the Connectivity Map – a graph representation of the collaborations between all Principal Investigators in the Laboratory. The graph, produced by Prof. Isaac Chuang and Dr. Orit Shamir, was based on joint publications and conference proceeding in the decade spanning 2002-2012, and provided an interactive tool to view and learn about the 130 distinct collaborations that have taken place between RLE members. The Connectivity Map supported the message of the RLE Fair, educating Laboratory members about other research groups, and promoting an interconnected community.

This year, RLE pioneered a study investigating the cost drivers behind on-campus renovations. The study was based on a collaborative approach, in cooperation with the Department of Facilities, in gathering data and jointly assessing the renovation process. With 101k ft^2 under management, RLE is a prime candidate for such an examination. RLE practices dynamic space allocation in support of new hires and current research needs, is home to diverse research areas, is large enough to be significant, but small enough to execute projects quickly and with expertise.

The study combined the renovation of new hire, Prof. Dirk Englund's, laboratory space with retrospective renovation data aimed at establishing the parameters for a low cost, high quality lab-based renovation model. The process achieved greater transparency into the renovation process, uncovered disputed issues in renovation procedures, promoted collaboration between a DLC and the department of Facilities, and established a lower price-point of operation with \$310/ft^2 for the Englund laboratory space. RLE looks forward to continuing these efforts by producing a streamlined, transparent renovation process, as well as a scalable solution for small project renovations.

In 2013, RLE instituted a central problem tracking system for Information Technology issues. The system allows us to track outstanding requests for service and gives us visibility into the daily workload of our staff. Since inception, over 3490 requests for service have been tracked. Over 70% of these requests were resolved in one day or less and 86% were solved in less than one week. The system is monitored daily to insure quality and timely delivery of Information Technology Services. Qualitative data extracted from the system has also helped us understand the types of problems we deal with and the number of issues submitted by our users. We use this information to help guide how we train our staff and pinpoint problem areas which can be addressed outside the system.

Until recently, RLE's business practices have been extremely paper-centric. A combination of historic business practices combined with MIT's retention policies necessitates collection of many paper documents. RLE has commenced a long term project named DigitalRLE; the project's aim is to substantially reduce the amount of paper collected. Phase one of this project was implemented in 2013 and involved ceasing the practice of collecting paper copies of Procurement Card receipts. RLE handle thousands of these receipts yearly requiring a substantial amount of clerical processing as well as archival storage. The new system as implemented requires all Procurement Card documents to be submitted electronically for central storage and verification. As of July 31, 2013, over 2000 digital receipts were submitted. RLE expects to enhance this system in the coming years and expand its use to other financial and human resource areas.

RLE offered a short course on project management, specifically for postdoctoral trainees. Twenty-two individuals participated in this pilot program which consisted of two half-day workshops. The program provided practical advice, tools and techniques for applying best practices in project management in the research group environment. The following key topics were covered: project leadership, communication and time management skills; project initiation, planning, implementation and closeout.

RLE launched a new Administrative Assistant Certification Program. This training program, consisting of monthly workshops, was created to support and enhance the administrative, human resources, fiscal and computer skills of the RLE's administrative assistants. The program began in summer 2012 and ended in early June 2013. 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 the following: Stellar course management, audits & compliance, performance reviews, RLE's digital and HR processes, WordPress web management, SAP reporting and processes, fabricated accounts, and Concur travel procedures. In order to receive the certification, assistants were required to complete nine out of twelve workshops. The following nine assistants were honored at a luncheon to acknowledge their achievement:

Donna Beaudry (Chan, Gallager, and Kolodziejski groups)

Dimonika Bray (Lang, Verghese, Schindall and Zahn groups)

Donna Gale (Kassakian, Kirtley, Leeb, and Perreault groups)

Cindy LeBlanc (Lim group)

Tricia O'Donnell (Wornell group)

Olga Parkin (Lu group)

Read Schusky (Dresselhaus group)

Laura von Bosau (Cappellaro, Kong, and Oppenheim groups)

Arlene Wint (Adalsteinsson, Braida, Shattuck-Hufnagel, and Stultz groups)

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, in the context of the limited pool of qualified technical applicants and the unique qualifications of RLE's sponsored research staff. Specific measures will include maintaining our high standards for recruitment procedures, among them sending job postings to minority colleges and organizations, working closely with the RLE faculty/staff supervisor at the beginning of each search to identify ways of recruiting minority and women candidates for the new position, and being committed to finding new techniques to identify women and minority candidates more effectively. During the past year, RLE has appointed three women to exempt-level staff positions in headquarters.

In addition, Maxine Samuels (financial coordinator) attended a leadership program that was offered through The Partnership, Inc. which is 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.

Cheryl Charles (fiscal officer) and Gabrielle Brewington (administrative assistant) chaired an employee resource group (ERG). An ERG is an employee-led group formed around common interests, issues and/or a common bond or background. ERG members create a positive work environment at MIT by actively contributing to the Institute's efforts specific to inclusion, such as recruitment and retention. Cheryl and Gabrielle organized a “speed networking primer” that served as an introduction to different career tracks at MIT. Mary Markel Murphy (assistant director for administration and human resources) was a panelist.

RLE has continued its work in nurturing future generations of engineers and scientists as evidenced by the activities highlighted below:

The Center for Ultracold Atoms (CUA) conducted a program to stimulate the careers of undergraduate physics majors who are thinking of becoming teachers in the physical sciences at the pre-college level. Called Teaching Opportunities in the Physical Sciences (TOPS), the program involved eight undergraduate physics majors, typically juniors, who were recruited from colleges and universities across the nation. These students worked in teams with two master teachers. The central activity in TOPS was the experience of actual teaching. Two teams of four students each worked under the direction of a master teacher to prepare and teach students at both 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. The program was free to the students. This was the 11th year in which CUA ran the program.

Professors Vladimir Bulovic and Yoel Fink hosted laboratory tours and research demonstrations for members of the American Junior Academy of Science which is under the umbrella of the American Association for the Advancement of Science (AAAS). These high school students reported that they had an amazing time and were thrilled to learn about cutting-edge research at MIT.

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

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