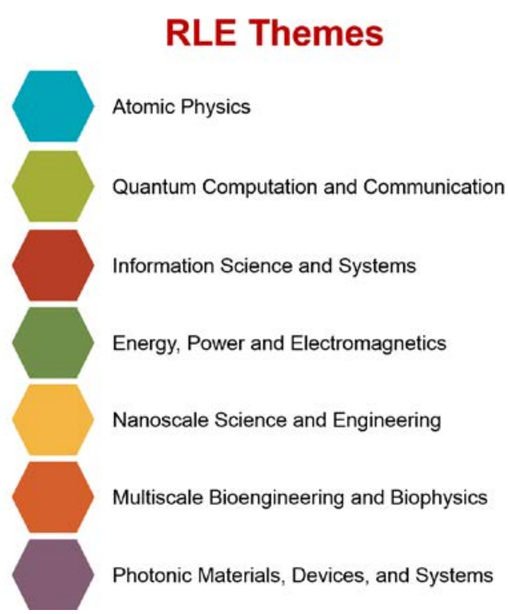
Research Laboratory of Electronics

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

RLE was founded in 1946 following the ground-breaking research that led to the development of ultrahigh frequency radar, a technology that changed the course of World War II. It has been home to some of the great discoveries made in the 20th century at MIT. With a research volume of $50.4 million in fiscal year 2017, the lab continued to be one of the Institute's leading research organizations. RLE manages more than 200 active research projects and services for over 70 principal investigators. In fiscal year 2017, RLE included approximately 275 graduate students and more than 75 undergraduates.



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

Laboratories and Research Highlights

Atomic Physics

Research in atomic physics at RLE encompasses 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, and many-body physics in lower dimensions, plasmas, and electromagnetics.

Professor Wolfgang Ketterle's research group is using ultracold atoms to explore new forms of matter at temperatures close to absolute zero. One recent result is the observation of the supersolid stripe phase in spin-orbit coupled Bose-Einstein condensates.

A supersolid is an unusual form of matter that combines the property of superfluid flow with the long-range spatial periodicity of solids. Though long predicted, the observation in solid helium has been elusive. The concept of supersolidity was generalized to include other superfluid systems that break the translational symmetry of space. One candidate has been a Bose-Einstein condensate with spin-orbit coupling where the stripe phase features a density modulation. We recently reported the first observation of this modulated density. For this, we used a novel spin-orbit coupling scheme developed in our previous work (Li et al., 2017) where the two pseudospins are the two lowest states in a lattice of double wells (superlattice). The new scheme allowed us to not only increase the contrast of the stripes but also gave us a background free signal. The associated density modulation was directly observed by light scattering. This work establishes a system with unique continuous symmetry breaking properties and associated Goldstone mode and superfluid behaviour.

The research of Professor Vladan Vuletic focuses on large quantum mechanical systems and how quantum correlations (entanglement) can be used to perform tasks that are impossible within classical physics. A particular focus is on how to use entanglement to improve atomic clocks and atomic interferometers, and to control photons individually. Recent highlights by the Vuletic group include the first observation of a bound state of three photons, the demonstration of a quantum simulator with 51 individually controllable interacting atoms, the observation of collisions between photons, and the first demonstration that a Bose-Einstein condensate can be produced by laser cooling alone.

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

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

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

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

The second breakthrough was achieved on our experiment on ultracold fermionic molecules. Molecules have long been proposed as a quantum resource for quantum information and computation. Their rich degrees of freedom—electronic, vibration, rotation, and nuclear spin—seem ideal for storing quantum information and also for implementing quantum gates. Last year we produced the first chemically stable Fermi gas of ultracold molecules. We soon gained control over their rotational and nuclear spin degrees of freedom via microwave drives, and were then able to produce quantum superpositions of nuclear spin states. We observed a record second-scale coherence time for this superposition in our gas containing several thousand molecules. This represents a thousandfold improvement in the coherence time of ultracold molecules and makes these molecules extremely interesting for quantum information applications. The long coherence times are owed to several facts: the absence of electron spin in the electronic ground-state of these molecules, only quadratic sensitivity to electric fields, and the fact that these molecules are fermions, and therefore they do not collide head-on. We believe that the combination of long storage times in nuclear spin states, and strong interactions between molecules induced by rotational transitions, could make molecules a promising platform for quantum information processing.

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

Energy, Power, and Electromagnetics

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

Professor James Kirtley of the Laboratory for Electromagnetic and Electronic Systems (LEES) is a specialist in electric machinery and electric power systems. Over the past year, his group has made progress in a number of different areas:

In a collaborative effort with Mohamed Al Hosani of the Masdar Institute in Abu Dhabi and Professor Konstantin Turitsyn of the Department of Mechanical Engineering at MIT, members of Kirtley's group have developed systematic methods for assessing and ensuring stability of microgrids supplied by inverter-based sources (such as solar, certain types of wind turbines, and microturbines). These types of microgrids are, somewhat counterintuitively, more likely to exhibit instability when closely coupled together. Results have been published and presented to the Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society.

Members of Kirtley's group are learning to use real-time simulation ("hardware in the loop") to assess the performance of control systems. Two Typhoon HIL devices have been acquired and put into use within the group. A specialized simulator that uses the type of control boards that were developed for the small-scale microgrid to emulate devices in a microgrid and a field programmable gate array to emulated KVL and KCL for the network is under development.

Kirtley's group has also been active in commissioning a real microgrid at the Stone Edge Farm in Sonoma, California. This system illuminates the sorts of challenges faced by real microgrids, in that it has several possible "masters" in a "master-slave" relationship, and some sort of higher level control is required to select which device is to be "master" at any given time. The microgrid is now working, data gathering devices are installed, and methods are developed for assessing the performance of the whole system.

A project to build and understand the operation of flux switching permanent magnet motors has been completed. This project was undertaken in an effort to build better motors for electric motorbikes. Kirtley's group built a motor similar to one that had been constructed but only partially tested at Southeast University in Nanjing. A postdoctoral researcher in Kirtley's group, Matt Angle, was able to run the motor satisfactorily. Another postdoc in the group, Ho-Tin Lee, has analyzed the motor type and explained its working in detail. Although the project has finished, the motor is still in a test facility and it is anticipated that more testing will be done on it.

As part of the Tata Center–supported collaboration with the Indian Institute of Technology, Bombay (IITB), Mohammad Qasim, a member of Kirtley's group is collaborating with Professor Vivek Agarwal of IITB in trying to design better (more efficient, higher-power-factor) single-phase motors for applications such as appliances, pumps, and perhaps most importantly, ceiling fans. A specialized dynamometer has been set up to measure the performance of ceiling fans.

Under the sponsorship of the MIT Energy Initiative, through a grant from the Bechtel foundation, a laboratory-scale microgrid setup has been built to support curricular improvement to 6.061 Introduction to Electric Power Systems. This facility was used during the spring term to demonstrate elements of electric power generation.

Professor Steven Leeb's group—also a part of LEES—has had an extraordinary year developing systems for controlling and generating energy. He and his team received US Patent 9,407,164B2 for a new circuit topology using switched DC-DC converters for optimizing power extraction from solar cells with uneven shading. This work connects solar cells at arbitrary levels from single cells to complex installations of panels with grid-tie inverters. The work was conducted in collaboration with Professor David Perreault's group. The patent describes switched capacitor circuits for optimizing performance in module, sub-module, and cell installations, including incorporation of the power electronics on the cell substrate.

The group also developed new mathematical techniques and circuits for noncontact power monitoring. These techniques can "scan" the inside of a complex cable to determine voltage and currents of a wire bundle without touching the wires. New algorithms and hardware have applied this technique to distribution voltage levels of thousands of volts. The *IEEE Sensors Journal* paper describing this work was recognized as one of the 25 "most downloaded" papers for the *IEEE Sensors Journal*.

Professor Leeb and his team developed a new power electronic technique for reducing the impact of constant power loads on the electric utility. Power electronic loads, like variable speed drives in air conditioners and lighting drivers for LED lighting, use active control to demand constant power from the utility. When the utility voltage drops, these loads increase their current demand, creating a potentially destabilizing response on the grid. New hybrid circuits developed and demonstrated this year maintain constant power to the load while presenting a resistive demand to the utility over short time scales. These loads maintain load operation while reducing their current demand when the utility voltage drops.

In addition, the group developed a new application of contracting systems theory, which is permitting fresh approaches to induction machine diagnostics in energy consuming systems. This work exploits the repetitive operation of periodic loads like compressors to make fine-grain determinations of diagnostic problems, before these problems are detectable by other means. For example, subtle valve failures in HVAC compressors have been determined using the technique, and new work is under way to extend the methods to critical process pumps in refining operations.

Lastly, the group secured over two million dollars in donations for reconstructing the physical space of the LEES laboratory. The reconstruction will result in a new state-of-the-art Grainger Energy Machines Facility upon completion of construction in Building 10.

Professor Jeffrey Lang's research focuses on the analysis, design, and control of electromechanical energy-conversion and motion-control systems. Its applications typically involve high-performance electrical machine systems, micro- and nano-scale electromechanical actuators and sensors, distributed electromechanical structures, or both. Illustrative examples of this research taken from the past year over a several applications are given below.

A team of graduate students and postdocs,under the supervision of Professors Vladimir Bulović, Timothy Swager, and Lang have continued to develop a NanoElectroMechanical (NEMS) relay that operates with an organic molecular monolayer between its contacts. Closing the relay is accomplished with electrostatic actuation, typically below one volt. When closed, the relay conducts via tunneling through the molecular monolayer; when open, its conduction reduces by a factor of approximately 10^6. The importance of the molecular monolayer is that it holds the relay together while preventing contact stiction, thereby eliminating a major impediment to using NEMS relays for low-voltage digital logic and RF switching. A major accomplishment of the past year was the demonstration of a four-terminal relay that isolates relay control from relay action, offering important circuit advantages. Analog extensions of the relay include high-gain, low-voltage valves. More generally, over the past year we have developed process steps enabling the fabrication of electrically adjustable, nanometer-scale gaps that are foundational to the aforementioned devices. The process steps involve chemical syntheses, self-assembly, continuum electromechanics, and molecular engineering, and have been demonstrated to be scalable to circuit-level complexity complete with device interconnects and electrically tunable nano-scale gaps for plasmonic applications. Current work focuses on reducing the actuation voltage and energy, improving fabrication yield, and simultaneously increasing the ratio of on-state to off-state conduction. Additionally, over the past year, the molecular layers used in our relays have been by used others allowing those relays to actuate at voltages approaching 25 mV.

Graduate student Matthew D’Asaro and undergraduate student Daniel Sheen, working with Professor Lang, have developed a low-cost sensory skin that can differentiate between pressure and shear in a distributed manner along the skin. The skin is based on a (meandering) one-dimensional deformable split electromagnetic transmission line. The transmission line is fabricated as a traditional shielded three-wire microstrip but with a compressible polymer dielectric. Stress applied to the surface of the split transmission line distorts the line, resulting in impedance changes that can be detected as functions of position by a frequency sweep of impedance. The advantage of such a sensor is that it measures deformation, and hence pressure and shear, in a distributed manner along the line through a single electrical connection, thus greatly simplifying readout. The sensor is also very rugged and has a simple (in principle) extension to a two-dimensional stress sensor. Applications range from providing a sense of touch to robot hands, reanimating touch in human limbs that have suffered injury, to the measurement of stress along an airfoil. Recent work has improved the selectivity and sensitivity of the sensor to pressure and shear, as well as its immunity to external disturbances, and has enabled its fabrication over wide areas. The longest transmission line stress sensor demonstrated to date is approximately 10 feet. Additionally, a fast algorithm has been developed to rapidly compute the applied pressure and shear from data collected as an impedance sweep over frequency. Finally, a means of slowing the electromagnetic waves as they propagate along the transmission line by doping the dielectric with nano-scale particles having an extremely high permittivity has been demonstrated. The advantage of this is that it lowers the frequency range for a given spatial resolution simplifying the readout electronics, or increases the spatial resolution at a fixed frequency.

Professor David Perreault’s research focuses on advancing power electronics technology and on the use of power electronics to benefit key applications. Major research thrusts include the development of extreme high-frequency power conversion to attain miniaturization and integration, development of power converters having greatly improved efficiency, and the use of power electronics to benefit applications such as solar photovoltaics and grid-interface power supplies. One valuable result this year has been the investigation and characterization of power magnetic materials for use at high frequency (HF, 3-30 MHz). This work, which has led to a conference paper and journal paper, is valuable for designing power electronic converters operating in the HF regime. Perrault and his team are using these results to develop universal-input power supplies for grid interface operating at HF having greatly reduced size and higher power densities (e.g., ~ 50 W/in^3, 2 to 4 times the state of the art). The researchers have also been exploring reconfigurable power circuit architectures that can provide high efficiency over wide operating ranges (e.g., in voltage, power, or both). One aspect of this investigation has led to a new topology for high-efficiency, large-step-down DC-DC conversion that preserves high efficiency over a wide power range. One prototype design for 380 V to 12 V conversion at 300 W (e.g., for efficient DC distribution to computer servers) yields a full-load efficiency of 96%, a peak efficiency of 97%, an efficiency of 93% at 10% load and an efficiency of 80% at 3.3% load.

Professor David Trumper is a member of LEES. His research is focused on precision mechatronics applied to a wide range of problems from health care to precision manufacturing. During this last year, Professor Trumper and his group have worked on several major projects.

His group has been studying the design of high-force linear motors for rapid and precise positioning in applications such as semiconductor manufacturing, with experimentally proven performance exceeding any commercially available linear motor.

In collaboration with Professor Linda Griffith, Trumper's group has been designing mechatronic solutions for novel multi-organ human tissue bioreactors. This research is creating micro-physiological systems for the in vitro study of human organ tissues such as lung, gut, endometrium, and liver cells. In another collaboration with Griffith and with Professor Rebecca Carrier of Northeastern University, his group is designing mechantronic solutions for micro-physiological systems for studying human gut behavior in the presence of gut bacteria, as well as gut and liver interactions.

Professor Trumper is also working with an industrial partner to design new types of magnetically levitated impellers for blood oxygenation pumping. In a collaboration with the Masdar Institute, Professor Trumper's group is designing new approaches for solar energy collection and storage in a molten salt system. Finally, in a new collaboration with MIT Lincoln Laboratory, Professor Trumper's group is designing a new type of momentum wheel for microsatellite attitude control.

Information Science and Systems

Research in this area spans a complete range of activities 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 ultra-high-speed and high-quality service guaranteed heterogeneous networks and their particular relevance to defense network and cybersecurity. Their work includes applications over satellite, wireless and optical communication, and heterogeneous data networks. The objective is to develop the scientific base needed to design data communication networks that are efficient, robust, and architecturally clean, as well as to study application scenarios and their modeling to enable research and development of the "right" network architecture. Their work in the past three years on heterogeneous networks has stimulated worldwide research in the area; notably in Singapore the government has started the "heterogeneous" project that involves industry, academia, and government research laboratories. Professor Chan's group is acting as adviser for the research. Their program and these other scientific investigations are vital to growing the capacity of the internet by orders of magnitude in the future, at lower cost per bit and smaller energy budgets.

A new direction for the construction of optical network architecture was launched in the past year. The name of this initiative is Cognitive Management and Control of Agile Dynamic Optical Networks and is the first program funded by the National Science Foundation in this area.

The optical network of the future will have approximately three orders of magnitude increase in data rates, mostly due to large transactions. These elephant flows need fast scheduling of network resources and agile network adaptations for congestion control, load balancing, and reconfiguration to cope with huge traffic transients and reconstitution for network resilience. This research is relevant to current software defined network (SDN) development as well as extensions to "orchestration," the current push to involve all layers particularly the optical physical and control layers beyond SDN. A cognitive network management and control system senses current network conditions and uses this information to satisfy overall performance goals. A major goal of a cognitive network is to use processed network state data (past and current)—such as traffic and flow patterns—to improve resource management and provide quick responses to transaction requests. The design of a cognitive network should consider the following questions:

- Should cognitive processes be centralized, fully distributed, or partially distributed?
- How should network state information be filtered as the amount of global information grows?
- How should network changes be synchronized among subnets and controllers?
- Can the network function well with under-sampled and stale link state data?

This will be the first comprehensive research on cognitive optical network management and control. With the fast dynamics noted, agile automated adaptation must replace the current slow management control practise often with a human in the loop. The fruit of this research will have implications far beyond optical networks. These techniques can be applied to next-generation wireless networks and electronic networks (using optics only as transport) confining the network management and control functions in Layer Three as in SDN. In addition, the cognitive technique as applied to detecting anomalies can be applied as an independent check of the integrity of SCADA systems (e.g., power grid), and provide fast recognition of extreme and black swan events.

The research will use techniques that are necessary to implement the following objectives:

- Infer network state based on traffic and active probing with sparse and stale data
- Decisions on fast agile scheduling of bursty large transaction requests, load balancing, reconfiguration, and restoration
- Predict intention of users and take or recommend appropriate actions, including information assurance functions such as recognition of attacks or compromised subnets and isolation of faulty entry points or subdomains and network reconstitution

Four commercial companies, Cisco, Ciena Corporation, Acacia, and Plexxi have expressed strong interests and support of this research. The formulation and performance results were given in July 2017 in a keynote speech at the joint Conference on Laser and Electro-optics and the Optical and Electronic Communications Conference in Singapore, which served as the first announcement of the research direction.

The Energy-Efficient Circuits and Systems Group, led by Professor Anantha Chandrakasan, investigates new circuit-level and architectural techniques to enable improvements in energy efficiency and security for a wide range of integrated electronic systems. Example application domains include security, energy harvesting, and wireless charging for the Internet of Things, multimedia processing, and biomedical electronics. One highlight from the group this year is the development of secure wireless communications for the Internet of Things.

Security is the most important consideration in future low-power wireless networks focused on connecting edge devices. Wirelessly connected sensor nodes collect sensitive data that must be communicated securely. It has been shown that life-critical implantable devices controlled over a wireless link can be attacked, motivating the need to establish end-to-end secure solutions.

The group is currently developing an ultra-fast hopping transmitter and a wireless protocol for energy-efficient, secure wireless communications. Our targeted frequency-hopping rate of 1 μs is 100 times faster than the commercially available integrated solutions. The extreme-rapid frequency hopping performance enables sending each message bit on a different frequency channel, going beyond the conventional packet-level frequency hopping, for example existing protocols such as Bluetooth Low Energy deploy packet-level frequency hopping with a hop period larger than 600 μs. These long-hop intervals allow an attacker to identify individual packets from the target device and selectively jam them. The ultra-fast frequency-hopping rate of the transmitter currently under development prevents jammers from accurately detecting a target transmitter's carrier frequency and initiating interference before the target's next hop. The co-development of RF architectures and wireless protocols offer new security paradigms for the next generation of wireless connectivity.

Students and postdoctoral researchers in the group include Rabia Tugce Yazicigil, Phillip Nadeau, Chiraag Juvekar, Daniel Richman, Kapil Vaidya, and Wendy Fernandez.

The research group of Professor Luca Daniel uses several engineering design applications to drive research in simulation and optimization algorithms and software.

Research efforts focus on the fundamentals of model-order reduction, matrix-implicit methods, fast techniques for solving integral equations, and uncertainty quantification. Some of the most interesting research directions during last year are described below.

Utilizing Macromodels in Floating Random Walk Based Capacitance Extraction. This first research result received the best paper award at the IEEE 2016 Design, Automation and Test Conference and Exhibition in Dresden, Germany. The group has developed a technique that employs macromodels in order to extend and improve by orders of magnitudes in speed the floating random walk (FRW) method for capacitance extraction. We can build macromodels for each substructure for which it is either necessary or convenient to hide its geometry details during capacitance extraction. This method has high potential for impact not only because of the improved performance but also because it can be used to extract capacitances for structure with encrypted substructures, and extend the FRW method's capability for structure with complex geometry or repeated layout patterns. The approach has been validated on structures including encrypted FinFET layout, complex geometry features, and cyclic layout patterns.

Big-Data Tensor Recovery for High-Dimensional Uncertainty Quantification of Process Variations. This second research result received the best paper award at the 2016 IEEE Workshop on Signal and Power Integrity, and was invited as keynote paper for *IEEE Transactions on Component, Packaging and Manufacturing Technology*, published in December 2016. Fabrication process variations are a major source of yield degradation in the nanoscale design of integrated circuits (ICs), microelectromechanical systems (MEMSs), and photonic circuits. Stochastic spectral methods are a promising technique to quantify the uncertainties caused by process variations. Despite their superior efficiency over Monte Carlo for many design cases, stochastic spectral methods suffer from the curse of dimensionality (i.e., their computational cost grows very fast as the number of random parameters increases). In order to solve this challenging problem, we have developed a high-dimensional uncertainty quantification algorithm using a big-data perspective. Specifically, we have shown that the huge number of simulation samples (e.g., 1.5×10^{27}) in standard stochastic collocation can be reduced to a very small one (e.g., 500) by exploiting some hidden structures of a high-dimensional data array. We have formulated this idea as a tensor recovery problem with sparse and low-rank constraints, and we have solved it using an alternating minimization approach. We were able to simulate efficiently ICs, MEMs, and photonic problems with over 50 independent random parameters, whereas the traditional algorithm can only deal with a small number of random parameters.

Professor Jacob White leads the Computational Prototyping Group with Professor Luca Daniel. Professor White spent his fall term sabbatical helping several of his former students at Q-bio, a start-up interested in simulation for medical imaging. At MIT, Professor White's educational focus has been on low-cost, maker-engaging design laboratories. His labs have played a central role in the revitalization of undergraduate classes in feedback control. White conducted two interesting experiments with low-cost hardware-centric edX classes (both with Joe Steinmeyer and Nicolas Arango), and in spring 2017 an experiment with hardware design in 8.02 Technology Enabled Active Learning (TEAL), with Peter Dourmashkin. The latter led to the Electrical Engineering and Computer Science–Physics agreement to offer a special section of 8.02 in spring 2018 in which six of the TEAL experiences will involve hardware design (e.g., resistor piano, neo-windmill, and wireless power).

In research, Professor White continued to collaborate on simulation for ICP desalination (with J. Han), and on hardware and software for background field tailoring in MRI shimming and signal suppression (with Arango, J. Stockman [Massachusetts General Hospital] and L. Wald [MGH]). However, Professor White's main research focus has been on applications for the Computational Prototyping Group's recently developed fast voxel-based, volume-integral methods. He co-led the development of MARIE, an MRI-specific EM field simulator fast enough to use in patient-specific scanner optimization. This was featured on the cover of the *IEEE Transaction on Biomedical Engineering* (with Athanasios Polimeridis [SkolTech], Elfar Adalsteinsson, Luca Daniel, and Lawrence Wald [MGH]). He has also been investigating the use of voxel-based methods for fast extraction from semiconductor process emulation, with applications in terahertz circuit and nanophotonic design (with Ruonan Han, Duane Boning, Luca Daniel, A. Yucel, and M. Kamon [Coventer]).

Voxel-based 3D structure generation is so fast and reliably automatic, it has become a standard in a broad range of applications including medical imaging-based anatomical reconstruction, 3D printer model creation, and virtual nanofabrication. Its speed has enabled engineers and clinicians with hand-held tablets to visualize designs, diagnose diseases, and even plan surgery. But they cannot easily see their structures in action, nor assess and optimize performance, even though such a capability would be disruptively enabling. The problem is that state-of-the-art 3D simulation software, often finite- or volume-element-based, is not automatic enough, reliably accurate enough, or fast enough. These 3D software tools are too mismatched to the billion-cube geometries produced by voxel-based structure generation, so simulations often take days. Instead, far better performance can be achieved by exploiting the voxelization, as in the recently developed FFT-accelerated volume integral equation methods (FFT-VIEM). For example, the FFT-VIEM approach, implemented in the open-source package MARIE, only needs minutes to accurately compute MR fields in a billion-voxel, human-head model. White and his group are now rapidly expanding the applications for FFT-VIEM, beyond MR field analysis, and are currently focusing two emerging applications in nanoscale manufacturing: integrated nanophotonics and terahertz circuits.

Professor Jeffrey Grossman and his team in the Grossman Group focus their efforts on the computational and experimental design of novel materials for applications in energy conversion, energy storage, and separations. Significant results from this year include spinning out a company based on their graphene-oxide membrane research, which showed that these membranes possess dramatically higher temperature and chemical resilience compared to traditional polymer membranes while exhibiting excellent rejection at the 12 nm scale. Further work in the group on separations has led to the successful demonstration of 2 nm rejection by a new nanoporous silicon membrane. In addition, the group has developed a new type of phase change material for storing thermal energy, where the melting point of the material can be controlled by light.

Professor Jae Lim's group is involved in the development of image and video processing methods. During the past year, they accomplished the experimental verification of a prediction from a simple model that was recently developed for color images. An accurate model for color images can be useful in processing color images in a variety of applications such as enhancement, restoration, and compression.

Professor Muriel Médard leads the Network Coding and Reliable Communications Group, a highly cooperative research group with collaborations that include the Computer Science and Artificial Intelligence Laboratory, the Microsystems Technology Laboratories, the Laboratory for Information and Decision Systems, Aalborg University, Alcatel-Lucent, Australian National University, Ben Gurion University, Boston University, the Budapest University of Technology and Economics, Brown University, the California Institute of Technology, Chinese University of Hong Kong, CodeOn, Draper Laboratories, Duke University, École Polytechnique Fédérale de Lausanne, Fraunhofer Institute, Harvard University, KTH Royal Institute of Technology, Maynooth University, Northeastern University, New York University, Pennsylvania State University, Stanford University, Steinwurf, TU Braunschweig, TU Dresden, Technion, Trinity College Dublin, and University of Auckland. The group's central theme is networking, with a special emphasis on new practical and theoretical developments in the area of network coding. Specific achievements during the past year include both theoretical and practical work in developing information-theoretic approaches to password protection; new algorithms for storage and distribution in volatile networks; applications of network coding in reliability of networks—particularly in satellite systems (the paper "Topologies for the Provision of Network-Coded Services via Shared Satellite Channels," SPACOMM 2017 was winner of a best paper award); and the use of network coding in fifth-generation heterogeneous wireless systems. Médard received the IEEE Information Theory Society Aaron D. Wyner Distinguished Service Award in 2017.

Professor Vivienne Sze and the Energy-Efficient Multimedia Systems Group focus their research on the development and implementation of energy-efficient and high-performance systems for various multimedia applications, such as computer vision, machine learning, and video compression. Their work traverses various levels of abstraction from energy-aware algorithm development for signal processing to efficient architecture design and low-power VLSI circuit implementation. The group's work this year has been concentrated in two areas: (1) energy-efficient algorithms for deep neural networks (DNNs), which give state-of-the-art accuracy on a wide range of machine learning tasks (e.g., object classification, speech recognition); and (2) joint architecture and algorithm design for energy-efficient, real-time visual inertial odometry (VIO) for drone navigation. Their work on designing energy-efficient DNNs using energy modeling and energy-aware pruning enabled a 3.7 times reduction in energy, which is 43% more energy efficient than previous state-of-the-art approaches. Additionally, their work on the co-design of algorithms and hardware for energy-efficient VIO (in collaboration with Sertac Karaman) makes it feasible to achieve real-time perception on a drone with less than 2 watts, which is an order of magnitude below existing off-the-shelf solutions. This is an important step toward enabling autonomous navigation for small, bottle-cap-sized drones.

Professor Gregory Wornell's research has focused on new technology and algorithms for advanced sensing and data acquisition, new techniques for computational imaging and vision in complex environments, and principles of learning in physical systems and embedded applications.

In the area of advanced sensing and data acquisition, he and his team have developed new techniques for optimizing antenna array design and sensor placement based on submodular function theory. Among other applications for these techniques, the group has shown how to incorporate a prior on the far-field so as to allow sparse arrays to be designed and arrays to operate efficiently at multiple wavelengths. In addition, the methodology enables the optimization of very large arrays subject to geographic constraints.

In the area of computational imaging in complex environments, we have developed a new imaging methodology for "seeing around corners," (i.e., non-line-of-sight optical imaging). In these settings, it is possible to measure the spatiotemporal patterns of reflected light from a diffuse intervening surface, but typically this results in a poorly conditioned inverse problem for scene reconstruction. The traditional solution to the problem has been to employ time-of-flight information to improve the conditions. However, this requires the use of high-speed pulsed lasers and high-resolution (picosecond) SPAD or other detectors, which are expensive and increase the system's complexity. The new methodology employed by the researchers does not require time resolution, but instead opportunistically exploits the presence of natural occluders on typical scenes. Paradoxically, such obstruction actually improves imaging performance and can be implemented with very low complexity.

Finally, in the area of learning in physical systems and embedded applications, the group has developed a powerful new information-theoretic framework for the design and analysis of learning techniques. As the basis of this framework, researchers addressed the problem of universal feature-selection from high-dimensional measurements. In contrast to traditional engineering systems, one must select features before knowing the application. From the solution to this problem arises a powerful learning methodology that is highly practical, leading directly to iterative learning algorithms that provide a valuable interpretation of currently popular deep-learning techniques. Fundamental to this framework is the concept of the singular value decomposition of a distribution, the theory and numerical methods for which were developed in the Wornell lab as part of this effort. More generally, the team has been pursuing several promising applications, ranging from next-generation ADC design, novel fault-tolerant digital circuit architectures, to high-performance computational sensing and imaging system design.

Professor Lizhong Zheng and his team continue to work on applying information theory to a broad range of new problems in data analytics, with a breakthrough on formulating a new vector form information metric. This information metric generalizes the conventional scalar measure of information volumes. It can be used to quantify the semantics of data. It is found that the optimization of this new metric has direct connections to the performance limits of a general class of universal inference problems. Efficient algorithms are developed and tested on a wide range of real-world data sets. This work, for the first time, gives a theoretic framework in which different data processing algorithms—such as principal component analysis, compressed sensing, and neural networks—can be compared and understood in a unified picture and potentially generalized and improved. This work is published in *ISIT 2017* and a journal paper was submitted to *IEEE Transactions*.

Biomedical Science and Engineering

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

The mainstay of Professor Elfar Adalsteinsson's research in the MRI group at MIT continues to be medical imaging with magnetic resonance. Two multi-institutional grants from the National Institutes of Health now support the work on fetal imaging and MRI of the placenta, respectively, which is conducted by teams of colleagues from MIT, Massachusetts General Hospital, and Boston Children's Hospital. Imaging in pregnancy is an underserved area relative to decades of productive developments for adult MRI, and the domain poses multiple open questions across disciplines of engineering, science, and clinical practice. Parallel transmission technology, quantitative MRI, and image reconstruction and machine-learning applications are active topics in the group.

The Bioelectronics Group, led by Professor Polina Anikeeva, is dedicated to the development of multifunctional and minimally invasive interfaces with the nervous system. In the past year, the group has collaborated with Yoel Fink's group, Fibers@MIT, at RLE and Gloria Choi's group, Choi Lab, at the McGovern Institute for Brain Research at MIT to demonstrate multifunctional, fiber-based probes capable of simultaneous recording and optical stimulation of neural activity as well as delivery of transgenes and pharmacological compounds into the brain of freely behaving mice. These probes have enabled "one-step optogenetics" experiments, in which expression of an optically sensitive ion channel, such as channelrhodopsin-2, is deterministically collocated with an optical waveguide and an array of recording electrodes. The high flexibility and miniature footprint of these probes afforded by polymers and custom-engineered conductive carbon composites permitted multiple simultaneous implantations into several brain regions, allowing for studies of neural projection circuits. These probes were applied to investigation of neural pathways involved in anxiety-related behaviors in mice. Similar probes that integrated low-impedance metallic, rather than composite electrodes were engineered to record not only isolated action potential (spiking activity) but also slow-varying local field potentials, which are known to have important roles in information propagation and processing. The prevalence of specific frequencies in these oscillations can also serve as a hallmark of a particular neurological condition (e.g., β-band in Parkinson's disease). Using our fiber-based probes we have demonstrated the ability to optically drive local field oscillations with high coherence across the entire physiological frequency spectrum 2-128 Hz.

Professor Lou Braida and the Sensory Communication Group investigate topics in three broad areas: hearing aids, the tactile communication of speech, and auditory-tactile interaction. Work during the past year was focused on hearing aids. The long-term goal of the hearing aid research conducted in the group is to develop improved aids for people suffering from sensorineural hearing impairments and cochlear implants for the deaf. Efforts are focused on problems resulting from inadequate knowledge of the effects of various transformations of speech signals on speech reception by impaired listeners, specifically on the fundamental limitations on the improvements in speech reception that can be achieved by processing speech. Key results during the past year were focused on the problems faced by hearing-impaired listeners for understanding speech in backgrounds of noise. The deterioration in speech intelligibility in noise is particularly acute for listeners with impaired hearing. In particular, these studies indicate that hearing-impaired listeners derive less benefit than normal-hearing listeners in the presence of intermittent noises. This most likely accounts for the dissatisfaction many impaired listeners experience with hearing aids. The team is developing a signal-processing technique that seeks to improve speech comprehension in environments with intermittent noise, such as in a restaurant. Results obtained with a real-time, signal-processing system indicate that this technique improves the performance of hearing-impaired listeners in fluctuating background noise, particularly for noises with periodic gaps. In addition, the group has initiated research on human subjects motivated by the discovery of noise-induced, cochlear synaptopathy in animals. In animals, this loss is characterized by normal thresholds of hearing and intact outer hair cells in the presence of damage to a particular type of auditory nerve fiber that encodes high-intensity sounds. Psychoacoustic tests were designed to probe the possible existence of cochlear synaptopathy in young adults with clinically normal hearing. The ability of these listeners was measured on two psychoacoustic tasks including detection of tones in noise and detection of amplitude modulation for masked tone complexes. Using three levels of tones spanning a 30-dB range, masked tone detection and masked three-tone discrimination were measured and changes in performance were assessed as a function of tone level. For each individual listener, these measurements were related across tasks to determine if performance on one task could be used to predict performance on the other task. Possible evidence of cochlear synaptopathy was present in several listeners who showed deteriorated levels of performance at the highest signal level on conditions from each of the two tasks. This research has implications for treatment of persons with hearing impairment and for the development of new types of hearing aids.

The research in Professor Dennis Freeman's group explored the cochlear mechanisms that underlie the extraordinary properties of our sense of hearing, focusing primarily on sensitivity to low amplitude sounds and to acute frequency selectivity, which are hallmarks of mammalian hearing. Previously, the group has shown that the tectorial membrane (TM), which is a gelatinous structure that stimulates the sensory receptor (hair) cells in the inner ear, supports traveling waves of motion, and that these traveling waves play a key role in shaping the frequency selectivity of hearing. Work during the past year has focused on understanding how other structures in the inner ear (such as hair cells and surrounding fluid) affect TM traveling waves. To that end, we have analyzed a viscoelastic model of the TM. Results demonstrate that hair bundle stiffness has little effect on TM waves, but viscous loss due to the surrounding fluid tends to decrease the wave decay constant. Increasing TM thickness tends to moderate effects of cochlear loads. As TM thickness increases, the wave decay constant approaches an asymptotic limit that is independent of cochlear loads. However, decreasing TM thickness below its naturally occurring thickness can drastically reduce TM wave propagation. These results help to explain systematic differences in TM thickness seen across species as well as differences across regions in the same species. Furthermore, they suggest an evolutionary pressure for the TM to be just thick enough to support traveling waves. These results could have application to the clinical diagnosis and treatment of hearing disorders.

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

Professor Fujimoto's group and collaborators were responsible for the invention of optical coherence tomography in the early 1990s as well as its commercialization by Carl Zeiss and its initial applications in ophthalmology. OCT has become a standard diagnostic procedure in ophthalmology and 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.

The group is continuing studies of OCT in ophthalmology in collaboration with the New England Eye Center, investigating structural and functional retinal imaging for disease pathogenesis and treatment response in age-related macular degeneration, diabetic retinopathy, and glaucoma, which are the leading causes of blindness. Working in collaboration with the VA Boston Healthcare System, the group is investigating endoscopic 3D OCT for detecting dysplasia in the upper gastrointestinal tract to guide biopsy and to assess ablative therapies such as radio frequency ablation for the treatment of dysplasia and cancer. The group is also working with collaborators at the Beth Israel Deaconess Medical Center using nonlinear microscopy for intraoperative evaluation of breast cancer surgical specimens in a clinical study aimed at reducing the rates of repeat surgeries.

Professor Fujimoto and Eric Swanson co-authored an invited paper for a special issue of *Biomedical Optics Express* commemorating the 25th anniversary of the invention of optical coherence tomography. The paper "The Ecosystem that Powered the Translation of OCT from Fundamental Research to Clinical and Commercial Impact," describes the history of OCT development and commercialization as well as its economic impact.

Professor Martha Gray leads the Biomedical Technology Innovation Group. Her research program focuses on formalizing approaches that drive innovation to create impact, particularly in the context of pre and postdoctoral research training. In July 2016, together with her colleagues, she founded MIT linQ, an open organization comprising programs that seek to change the paradigm for research and training. The highlights of these programs include the following:

- The Catalyst program celebrated five years of success: increased pace and volume of innovation (e.g., licenses and start-ups per dollar of research investment is many fold greater than MIT overall); opened new lines of work (for 75% of the more than 130 collaborators), and attracted significant new funding (approximately $15 million) thanks to the $20 million investment by the community of Madrid.

    - Team Fetal, which aims to assess placental function to determine if early delivery is needed, received a multimillion U01 grant from the National Institutes of Health (NIH).

- Team neuroQWERTY, received a grant from the Michael J. Fox Foundation to support the further development of their technology to detect Parkinson's disease through natural interactions with a computer keyboard.
- Team Hydration received a point-of-care grant from NIH to develop a device that can measure hydration in vulnerable populations, such as older people in care facilities for whom dehydration can lead to reduced mental function and falls.

- MIT IMPACT program launched: Piloted in 2014–15 through MIT's Innovation Initiative, this research career development program is officially launched thanks to a five-year NIH grant. The program now runs two editions a year, with 24 participants each, and involves mentors from throughout the local biomedical community.
- IDEA² Global program launched to provide mentoring and connections to biomedical innovators around the world to develop their project ideas and to provide the expertise to realize them. IDEA² Global evolved from two prior programs, IDEA² at HST, and IDEA² Madrid, and was suported by corporate funding. There were about 50 applications for 15 available positions offered to the 2016 class.

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

Since 2010, professor Han and his team have been investigating ion concentration polarization (ICP) desalination, which is a novel electrical desalination technique. In recent papers the team elucidates the unique advantages of ICP desalination over conventional electrodialysis. In a paper by Rhokyun Kwak and others, it was shown that ICP desalination enjoys enhanced salt removal ratio over electrodialysis given the same operating current due to its unique unipolar ion conduction design. This can translate into up to 50% less energy consumption compared with electrodialysis, with all other conditions being equal. In a paper by Bumjoo Kim and others, it was shown that ICP desalination can be used to treat brine (wastewater that is saltier than seawater) more economically than available techniques. Brine wastewater treatment is gaining importance in conventional desalination, oil and gas, and mining industries, but currently the cost of treating (desalinating) brine is prohibitively high. The team hopes to further engineer the technique to be used for such challenging water treatment problems in the future. The research was supported by the Kuwait-MIT Center for Natural Resources and the Environment, which was funded by Kuwait Foundation for the Advancement of Sciences.

Professor Thomas Heldt directs the Integrative Neuromonitoring and Critical Care Informatics Group. Using physiologically based dynamic models, his group leverages multivariate bedside monitoring data—on the second to hour timescale—to understand the physiology of the injured brain, to improve diagnoses, and to accelerate treatment decisions in the critically ill. A key research accomplishment over the past year has been further improvements in the group's model-based noninvasive and patient-specific approach to intracranial pressure estimation, specifically in pediatric patients. Additionally, the group's work has led to the filing of three patent applications over the past year.

Professor Thomas Heldt's group continues very strong and active collaborations with clinicians at Boston Children's Hospital, Boston Medical Center, Massachusetts General Hospital (MGH), and Beth Israel Deaconess Medical Center in the areas neurocritical and neonatal critical care as well as other areas of patient monitoring. The group's collaborative work with MGH on developing an early warning system for sepsis has led to a reduction in the (median) time to appropriate antibiotic administration in septic patients in the MGH Emergency Department by almost an entire hour. This is highly relevant as each hour of delay in the administration of appropriate antibiotics in septic shock patients has been shown to increase mortality by over seven percent.

Group member Rebecca Mieloszyk completed her PhD this year on assessing levels of sedation in patients under anesthesia, and her thesis was awarded the 2016 Jin-Au Kong Prize for an outstanding doctoral thesis in electrical engineering. Rohan Jaishankar submitted his SM thesis, and Jonathan Birjiniuk submitted his MEng thesis. Additionally, Birjiniuk was awarded the Thomas (1959) and Sarah Kailath Fellowship, and incoming graduate student Syed Imaduddin was awarded a Grass Instruments Graduate Fellowship—both from the Department of Electrical Engineering and Computer Science.

Professor Timothy Lu's Synthetic Biology Group seeks to construct and re-encode biological systems from the ground up. Six major advances, published this year, are briefly described below.

Therapeutic antibody cocktail produced in yeast. The 2013 Ebola outbreak highlighted the limited treatment options and lack of rapid response strategies for emerging pathogens. We introduced a genomic landing pad in Pichia pastoris for reliable, recombinase-mediated DNA integration. The glycoengineered yeast produced monoclonal antibodies comprising the ZMapp cocktail for which we demonstrated binding to the Ebola virus glycoprotein. This approach could accelerate the production of therapeutics in future outbreaks of infectious disease.

Optical detection of proteins. Protein expression and secretion guide a significant aspect of nearly every cellular metabolic or signaling pathway. Aberrations in protein expression, for example, can indicate disease. To address the need for label-free optical detection of specific proteins from unpurified biological samples, we developed a platform consisting of a nanosensor array made by conjugating an aptamer-anchor polynucleotide sequence to single-walled carbon nanotubes and optimizing sensor response with a variable chemical space. With this platform we could measure protein efflux from individual bacterial and yeast cells immobilized in a microfluidic chamber. The two proteins tested were selectively detected via near-infrared fluorescent turn-on responses. A unique protein resulting from bacteriophage infection of E. coli was also detected with this potentially versatile nanosensor array.

Stretchable biocompatible hydrogel-elastomer hybrid. Freestanding materials and devices frequently undergo deformation during applications, compromising the viability, functionality, and safety of living components within them. To overcome this limitation, we designed hydrogel-elastomer hybrids that house genetically engineered bacterial cells, enabling living materials to be genetically programmed with synthetic circuits that execute sensing, computing, memory, and response functions. The hydrogel supplies water and nutrients, and the air-permeable elastomer maintains the long-term viability and functionality of the encapsulated cells. Bacteria in the hydrogel communicate with the environment via the diffusion of molecules. These stretchable living sensors respond to multiple chemicals. A quantitative model we developed can guide these hybrid designs.

Engineered nanofibers. Cell-synthesized amyloid nanofibers can be used to interface abiotic and biotic systems to create living functional materials. Amyloids are highly ordered, hierarchical protein nanoassemblies. One type of amyloid is curli fiber, found in *E. coli* biofilms and formed by the polymerization of monomeric proteins secreted into the extracellular space. We have engineered curli fibers to mediate tunable biological interfaces with inorganic materials. We used cell-synthesized curli fibers as templates for nucleating and growing gold nanoparticles and showed that nanoparticle size could be modulated as a function of curli fiber gold-binding affinity. We created artificial cellular systems that integrate inorganic and organic materials to achieve tunable electrical conductivity.

Mammalian synthetic cellular recorder integrating biological events (mSCRIBE). Technologies that enable the longitudinal tracking and recording of molecular events into genomic DNA could be used to monitor cellular states in artificial and native contexts. We have developed mSCRIBE, a memory system for storing analog biological information in the form of accumulating DNA mutations in human cells. mSCRIBE leverages self-targeting guide RNAs (stgRNAs) that are engineered to direct streptococcus pyogenes Cas9 cleavage to DNA loci that encode the stgRNAs, thus mutations accumulate at stgRNA loci as a record of stgRNA or Cas9 expression and localized, continuous DNA mutagenesis is a function of stgRNA expression. In vivo recording of molecular events (e.g., with mSCRIBE) makes it possible to monitor signaling dynamics in cellular niches and critical factors orchestrating cellular behavior. With mSCRIBE, programmable and multiplexed memory storage in human cells can be triggered by exogenous inducers or inflammation in vitro and in vivo. mSCRIBE provides a distinct strategy for investigating cell biology in vivo and enables continuous evolution of targeted DNA sequences.

Recombinase-based state machines. State machines underlie the sophisticated functionality behind synthetic and natural computing systems that perform order-dependent information processing. By leveraging chemically controlled DNA excision and inversion to encode states in DNA sequences, we developed a recombinase-based framework for building state machines in living cells. The readout is done by sequencing the polymerase chain reaction. We validated our framework by engineering state machines in E. coli that used one, two, or three chemical inputs to control up to 16 DNA states. These state machines could record the temporal order of all inputs and perform multi-input, multioutput control of gene expression. We also developed a computation tool for the automated design of gene regulation programs using recombinase-base state machines. Our scalable framework should enrich our understanding of how combinatorial and temporal events regulate complex cell functions and program cell behaviors.

Principal Research Scientist Stefanie Shattuck-Hufnagel's research group had three major themes this year on developing integrated models of the production, perception, and learning of speech:

- Development of a feature-cue-based speech analysis system to serve as a model of the initial stages of human speech recognition
- Testing the role of rhythm, periodicity, and motor entrainment in the organization of speech and non-speech behaviors
- Investigation of the alignment between co-speech gestures of the hands with spoken prosody to facilitate a comprehensive model of speech production planning that includes the sentence, its prosody, and its gestures

The overall goal of this work is to integrate relevant findings across the disciplines of acoustics, computer modeling, linguistics, psycholinguistics, and neurocognition to generate a computer-implemented model of human speech-related processes. This approach can benefit both the development of effective new tools for clinical intervention and the improvement of current algorithms for automatic speech recognition, as well as potentially enabling the teaching of second languages that reduces or eliminates a foreign accent.

This year's successful implementation of the LEXI system for speech analysis (for linguistic event extraction and interpretation) is due to the leadership of Jeung-Yoon Elizabeth Choi PhD '99 who supervised the work of nine students participating in the Undergraduate Research Opportunity Program (UROP), three SuperUROP students, and two master's degree students. It is the culmination of many decades of work in our laboratory, uniting the insights of linguistic phonology, acoustic phonetics, cognitive modeling, and recent developments in machine learning. In our ongoing work, the LEXI system provides a test bed for modeling additional steps in the human word-recognition process, including whole-phrase recognition that is heavily influenced by knowledge-based prediction.

Additional work includes an investigation of the development of feature-cue-based signaling in the speech of children, and preparation of two books: the volume *Speech Timing*, with Alice Turk (University of Edinburgh) for Oxford University Press, and the edited volume *Prosodic Theory and Practice*, with Jonathan Barnes (Boston University), for MIT Press. Finally, Shattuck-Hufnagel has been invited to give the keynote address at the annual meeting of the Linguistic Society of American in January 2018.

Professor Collin Stultz and the Computational Biophysics Group are focused on the development of computational tools that: (1) improve our understanding of fundamental biochemical processes that play a role in human disease; and (2) use machine learning to improve the care of patients with cardiovascular disease.

The overall goal is to develop an improved understanding of disease processes at the molecular level and use these new insights to build novel therapies. The group's approach involves both the building of computational and theoretical models and conducting biochemical experiments that are designed to test and refine these models. In this regard, we have developed a deep interest in understanding the structure of intrinsically disordered proteins that are involved in human disease. Over the past year, we have applied our methods to understand the unfolded state of a potent toxin/anti-toxin system, and published our results in the *Journal of the American Chemical Society*. These results are important because toxin/anti-toxin systems are present in many different pathogenic bacteria and form a potential platform for the design of novel antimicrobial agents. The group has presented seven invited talks on biophysical studies since 2016 at national and international meetings, such as the American Chemical Society National Meeting, the John's Hopkins Distinguished lecture series, and the Biophysical Society Thematic Conference in Berlin, Germany, among others.

The team is interested in using machine learning to identify patients who are at high risk of cardiovascular death after an acute coronary syndrome—an often catastrophic event. Developing methods to improve care for patients with cardiovascular disease remains an important goal of the laboratory. The lab recently built a software tool that uses electrocardiographic data to predict adverse outcomes in patients who have suffered an acute coronary syndrome. This research was published in *Nature Scientific Reports*. In addition, the group has submitted a large grant in conjunction with Brigham and Women's Hospital to develop machine-learning approaches to aid patient risk stratification and treatment.

The Computational Physiology and Clinical Inference Group directed by Professor George Verghese is focused on bedside informatics: using physiologically based dynamic models to interpret—on a timescale of seconds to minutes to hours—the multivariate monitoring data collected in settings ranging from acute care to home monitoring. The group interacts closely with Professor Heldt's research group on integrative neuromonitoring and critical care informatics. Several clinical collaborators also participate in the research.

An important research direction is aimed at more extensive and refined use of time-based capnography, which records the partial pressure of CO_2 as a function of time in exhaled breath. Capnographs are ubiquitous in hospital settings and ambulance systems, but only a fraction of the information available in the capnogram is currently extracted and used. This research is being carried out with the close involvement of Baruch Krauss at Boston Children's Hospital and of his clinical collaborators in various hospitals (Philadelphia; Vancouver; and Trieste, Italy), who have collected valuable original data for the studies. The doctoral thesis work of Rebecca Mieloszyk "Learning and Model-Based Approaches to Improved Patient Monitoring, Assessment, and Treatment in Capnography and Procedural Sedation," performed under the co-supervision of Professors Heldt and Verghese, was submitted in August 2016 and earned the Department of Electrical Engineering and Computer Science's Jin-Au Kong Award for outstanding thesis in electrical engineering. The thesis developed automated tools for preprocessing the capnogram—collected in a noninvasive and effort-independent manner during a few minutes of normal breathing—and extracting physiologically relevant features, followed by machine learning algorithms that classify the capnogram. The approach is able to distinguish, with good accuracy, patients with chronic obstructive pulmonary disease (COPD) from those with congestive heart failure, even though these two groups can present to the emergency department with very similar symptoms, and to distinguish COPD from healthy subjects with very high accuracy. The thesis also studied the use of capnography as well as pharmacokinetic modeling to monitor depth of sedation in procedural sedation. The group's research has now expanded to developing simple mechanistic models for the capnogram, with clinically meaningful parameters that can be identified in real time during patient monitoring. A paper demonstrating the success of this approach, "Model-Based Estimation of Respiratory Parameters from Capnography, with Application to Diagnosing Obstructive Lung Disease," written with former student Abubakar Abid, has just been published in the *IEEE Transactions on Biomedical Engineering*.

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. Professor Voldman and the Biological Microtechnology and BioMEMS Group have been working on several areas this past year. One is the culmination of a multi-year effort to create sensors that can determine whether engineered systems affect the cells they are meant to manipulate, such as cell sorters. The group created a suite of cells that glow different colors when they experience various stresses, allowing the engineer or end user to quickly determine if a system exposes cells to excess heat, liquid flows, and so on. These cells are available to the community and a paper has been published in *Analytical Chemistry*.

Another area of research has been to develop ways to measure multiple physical properties of cells. Professor Voldman's group has been working on a suite of different approaches to this problem, which could enable quick analysis of cells for a variety of medical conditions, from cancer assessment to monitoring of infections. One such method, where cells are tracked as they traverse a playground of different measurement structures, will be described in an oral presentation at the 2017 microTAS Conference, the premier international conference in microfluidics.

Nanoscale Materials, Devices, and Systems

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

Professor Karl Berggren's research group develops nanofabrication methods for applications in quantum and nanotechnologies. The main areas of research focus are superconducting nanotechnologies for radiation detectors, quantum circuits, and superconducting nanoelectronics, as well as investigation of fundamental interactions of electrons, ions, and photons with matter for applications in lithography, microscopy, and nanofabrication.

Professor Berggren's group has recently developed a single photon imager that can detect where and when a single photon comes. The entire imager is made from a single 300-nm-wide nanowire meandering over an area of 286 × 193 μm2 with a total length of 19.7 mm. This scale is equivalent to a 151-mile-long path for a 12-foot-wide highway lane. The readout uses a distributed fashion, which means that the output pulses from both ends provide the location and time of the detection events by their propagation times. It is feasible because they control the speed of the microwave propagating in this long superconducting nanowire at 2% of the speed of light, which is only 6 μm per picosecond. With this technology, Professor Berggren's group has demonstrated imaging of an array formed into the MIT logo at an extremely weak illumination—only one photon was counted within approximately 1 ms. With their achievements, it is now possible to have a single-photon imager of thousands of pixels. They expect the imager to become a powerful single-photon-detection tool in areas such as quantum information science, deep space communications, biological imaging, and spectroscopy, as well as in astronomical observation.

Over the past year, in addition to developing nanowires for single-photon detection and image, Professor Berggren's group also developed a group of superconducting nanodevices for high-speed and energy-efficiency computing. Their devices are named honoring the original cryotrons that were invented by Dudley Buck at MIT back in the 1950s. Based on the device's structure and operation mechanism, they have developed nTrons (nanocryotrons) and yTrons (current crowding cryotrons). With these nanowire cryotrons, his group demonstrated superconducting logic circuits, memories, and superconducting quantum interference devices. By linking millions of such devices, they hope to have a superconducting computer with 100-times-faster calculation speeds while consuming much less energy.

On the nanofabrication side, Berggren's group has recently shown a nanofabricated, monolithic, path-separated electron interferometer. The interferometer consists of two 45-nm-thick silicon layers separated by 20 µm. This interferometer is fabricated from a single-crystal silicon cantilever with advanced focused-ion-beam milling technology. Using this interferometer, they have obtained interference fringes in a Mach-Zehnder geometry in an unmodified 200 kV transmission electron microscope. They envision this technology would be used in electron holography, or as a platform to investigate fundamental physics experiments, such as interaction-free measurement with electrons.

The world of quantum mechanics holds enormous potential to address unsolved problems in communications, computation, and precision measurements for Professor Dirk Englund and his research group. Efforts are under way across the globe to develop such technologies in various physical systems, including atoms, superconductors, and topological states of matter. The Englund group is pursuing experimental and theoretical research toward quantum technologies using photons and semiconductor spins, combining techniques from atomic physics, optoelectronics, and modern nanofabrication. Some of last year's major research accomplishments are listed below.

A central goal in quantum information science is to develop a "quantum internet"—a layer of networked quantum computers operating alongside today's "classical internet." This quantum internet would allow a host of new technologies, including provably secure cryptography, distributed quantum computing, or ultra-precise global positioning systems. The Englund group developed an important step toward mass manufacturing of suitable solid-state quantum memories connected to optical fiber links, as well as the world's leading diamond nanocavity spin-photon interfaces.

Confining optical fields to small volumes is important for a number of applications, such as frequency conversion and two-qubit quantum gates. Previously, few-photon-level nonlinearities were reserved to the realm of esoteric physical systems, such as ultracold atoms. The Englund group developed a new concept to produce few-photon-level nonlinearities using an optical nanocavity that squeezes light by several orders of magnitude below the optical wavelength limit. Unlike previous approaches, this concept can operate at room temperature and uses common materials such as silicon.

Artificial intelligence is emerging as one of the key technologies of the 21st century. However, today's digital electronic computers are inefficient for AI algorithms, such as artificial neural networks. The Englund and Soljacic groups developed a new artificial coherent neural network architecture that uses optics to produce the connectivity of neurons. Optical links have major advantages for this connectivity over electrical connections as they can implement matrix products at extremely low power consumption and virtually instantaneously. Our RLE students won major business competitions based on this concept, including the MIT $100K Entrepreneurship Competition, the Harvard President's Innovation Challenge, the MIT Sandbox Innovation Competition, and are currently talking to several venture capital investors in the Boston and Silicon Valley areas about a possible startup.

The Englund group demonstrated a new type of quantum simulation circuit to study quantum transport, which is relevant in a number of physical processes such as photosynthesis. The group's approach uses photons passing through a programmable quantum walk developed in silicon photonics. Future work will study quantum walks of multiple identical photons, which were predicted by Professor Scott Aaronson and Alex Arkhipov to be extremely difficult for classical-physics supercomputers.

Over the past years, the Englund group has worked with Lincoln Laboratories to establish a quantum optical fiber network in the Boston area. This network was used for field trials of two types of quantum secure communication protocols—one using a novel high-dimensional encoding scheme, the other using silicon photonics-based transmitters. Both demonstrations set new records in bit rate. These mark important steps toward continent-spanning quantum networks.

A major new direction in the Englund group is to develop ways of patterning atomically thin 2D materials with atomic precision, to produce "ideal quantum materials" with desired properties engineered atom-by-atom. An encouraging step in this direction is the Englund group's recent demonstration of strain-tunable, ultrabright single-photon sources based on atomic defects in the 2D material hexagonal Boron nitride.

A collaboration between Professors Pablo Jarillo-Herrero and Englund has resulted in an important advance in chip-integrated infrared light sources and photo-detectors, using a novel atomically thin semiconductor junction integrated into a silicon photonics architecture. This work marks an important step in the development of atomically thin semiconductors in communication and computing systems.

Professor Englund is the principal investigator of the Air Force Office of Scientific Research Multidisciplinary University Initiative program Optimal Measurements for Scalable Quantum Technologie and a new National Science Foundation program, Emerging Frontiers Research and Innovation, on quantum repeaters, which include principal investigators from MIT and collaborators from Harvard, Yale, and the University of Maryland.

Professors Seth Lloyd and Englund co-organized the "Future Directions of Quantum Information Processing Workshop" in Arlington, VA, as part of a series of workshops sponsored by the Office of Basic Research on emerging areas of science that are a focus of the Department of Defense research portfolio. This workshop assembled leading researchers in quantum information science and quantum technology. The final report, "Future Directions of Quantum Information Processing: A Workshop on the Emerging Science and Technology of Quantum Computation, Communication, and Measurement," has been cleared for release.

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 toward realizing sophisticated functions are utilized: on the single-fiber level, the integration of a multiplicity of functional components into one fiber, and on the multiple-fiber level, the assembly of large-scale fiber arrays and fabrics. These multi-material fibers offer unprecedented control over material properties and function on length scales spanning the nanometer to kilometer range.

In 2016, Professor Fink led a $330 million winning proposal for the formation of Advanced Functional Fabrics of America (AFFOA), a Manufacturing USA Innovation Institute on revolutionary fabrics and textiles. AFFOA is dedicated to the mission of enabling a manufacturing-based revolution by transforming traditional fibers, yarns, and fabrics into highly sophisticated, integrated, and networked devices, systems, and products while strengthening the domestic supply chain in this area. Its broad-based support from government, industry, and academia is a testament to the Institute's vision and goals. Over the last year, AFFOA has become an established nonprofit, making remarkable progress in membership accrual and engagement, and unprecedented evolution of demonstrator projects.

Fink's research has also formed the basis for the NSF Materials Research Science and Engineering Center independent research group on fiber fluid instabilities joined in by other RLE principal investigators Polina Anikeeva, John Joannopoulos, Steven Johnson, and Marin Soljačić.

The research of Professor Jing Kong and the Nanomaterials and Electronics Group focuses on the challenge of developing the chemical vapor deposition (CVD) synthesis routes of various two-dimensional materials, characterizing their structures and properties and developing their applications. They are designing new strategies to make graphene, MoS2, and other novel 2D materials with desired physical, chemical qualities. The in-depth understanding in how to make such materials is enabling them to develop brand-new architectures for high-performance electronics and energy conversion.

The research focus in the group has been on two areas: large area chemical vapor deposition synthesis of two-dimensional materials, and development of highly porous, low density, high surface area aerogel materials. During the past year, the following topics were carried out within those two areas:

- CVD synthesis of monolayer 2H and 1T′ phase MoTe2
- Investigation of the Schottky junction between graphene and perovskite
- CVD synthesis of other transition metal dichalcogenide, such as VS2 and TiS2
- Direct synthesis of patterned MoS2 Kirigami Nanostructures
- Constructing aerogel materials from M13 virus and use that as a scaffold for functional inorganic materials

The Kong group had several interesting results during the past year. They successfully developed a procedure to coat perovskite films directly onto graphene without any interfacial hole transport layer. In this way, a Schottky junction is formed between the perovskite and grapheme. The group was able to characterize this Schottky barrier junction through CV measurement and further confirmed that perovskite as a semiconductor is free carrier-based instead of exciton-based. They have continued their aerogel investigation and collaborated with Professor Angela Belcher's group to develop M13 virus based aerogels (since the M13 virus is rod shaped with a long aspect ratio—very suitable for constructing aerogels). Since the surface functional groups of M13 virus can be engineered to capture various inorganic nanoparticles, these M13 viruses can be used as a scaffold for different functional inorganic materials such as metallic nanoparticles or magnetic nanoparticles, to be used as porous electrodes in batteries or for actuator applications.

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

Promoting the oxygen evolution reaction (OER) on metal oxides is essential to develop efficient energy storage technologies. The lack of efficient, stable, and cost-effective catalysts for the OER currently hampers the practical use of devices such as electrolyzers, metal-air batteries, photo-electrochemical water splitting, and CO_2 reduction. Recently the group has reported direct evidence challenging the traditional understanding that the OER mechanism on metal oxides involves only oxygen from water and the metal site from catalysts. Using an isotope tracking method, researchers showed that molecular oxygen generated during the OER on some highly active oxides can come from the oxide lattice. This observation provides, for the first time, experimental evidence of lattice oxygen redox reactions in metal oxides during the OER. By combining electrochemical characterizations with theoretical calculations, the group also demonstrated that the bulk electronic structure, and in particular metal-oxygen covalency, not only governs the OER activity but the reaction mechanism as well. Critically, the participation of lattice oxygen in the OER mechanism is associated with the decoupling of proton and electron transfers on the oxide surface, which has often been neglected in previous electrochemical studies. These new insights into the relationship between OER mechanism, kinetics, and material properties highlight new avenues for catalyst materials design, engineering the oxide anionic redox properties to develop highly active OER catalysts. The paper "Activating Lattice Oxygen Redox Reactions in Metal Oxides to Catalyse Oxygen Evolution," was published in *Nature Chemistry* in 2017.

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.

Professor Marc Baldo is the director of the Department of Energy–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 coupling between silicon solar cells and singlet exciton fission in the molecular semiconductor tetracene. Originally proposed by D. L. Dexter in the 1970s, this coupling promises to increase the maximum efficiency of silicon solar cells to over 30%. The fission process is used to effectively double the photocurrent obtained from the blue and green portions of the visible spectrum. The coupling was achieved using thin layers of titanium nitride. The mechanism is presently unknown and will be the subject of future work.

A second result is the report of an integrated organic functional material design process targeting novel thermally activated delayed fluorescence organic light emitting diode (OLED) emitters. In work performed together with the group of Professor Alan Aspuru-Guzik (Harvard), researchers demonstrated a selection sequence incorporating theoretical insight, quantum chemistry, cheminformatics, machine learning, industrial expertise, organic synthesis, molecular characterization, device fabrication, and optoelectronic testing. After exploring a search space of 1.6 million molecules and screening over 400,000 molecules using time-dependent density functional theory, the group identified thousands of promising novel OLED emitter molecules across the visible spectrum. The best candidates from this set were selected using the domain expertise from synthetic chemists, device scientists, and industry partners. Excellent predictive power has resulted in devices, with over 22% external quantum efficiency. Nearly 1,000 of the identified molecules across the visible spectrum are expected to match or surpass this performance. These results suggest that computational exploration of chemical space can be leveraged not only to single out promising new molecules, but also to reveal fundamental chemical insight. This approach is universal and might be applied in areas such as catalysis, high-performance materials, or polymers, where predictive theory, state-of-the-art computer science and accumulated chemical intuition can be combined to expedite discovery. The paper "Design of Efficient Molecular Organic Light-Emitting Diodes by a High-Throughput Virtual Screening and Experimental Approach," was published in *Nature Materials* in 2016.

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

Over the past year the Bulović group in collaboration with Keith Nelson's and Moungi Bawendi's groups devised a method to expose CdSe–CdS core–shell colloidal semiconductor quantum dots (QDs) films to high-field THz-frequency electromagnetic pulses whose duration is only a few picoseconds. In response to the THz excitation, the group was surprised to observe QD luminescence, even in the absence of an external charge source or presence of other high-energy photons that would typically be needed to generate excited QD states that can luminesce. The group's experiments show that the incident THz radiation results in a remarkably high and rapid modulation of the QD bandgap, which is changing by more than 0.5 eV (corresponding to 25% of the unperturbed bandgap energy) within the picosecond timeframe of THz field profile. We show that these colossal energy shifts can be consistently explained by the quantum confined Stark effect. Our work demonstrates a route to extreme modulation of material properties without configurational changes in material sets or geometries. Additionally, we expect that this platform can be adapted to a novel compact THz detection scheme where conversion of THz fields (with meV-scale photon energies) to the visible/near-IR band (with eV-scale photon energies) can be achieved at room temperature with high bandwidth and sensitivity.

Professor Peter Hagelstein's group has continued theoretical and experimental studies related to condensed matter nuclear science, which includes cold fusion and a variety of related anomalies.

Phonon-nuclear interaction. New models for nonrelativistic and relativistic quantum composites have found a relativistic interaction between the center of mass and internal degrees of freedom. This interaction can be rotated out in free space, but in the case of nuclei in a lattice, the interaction gives a coupling between vibrational motion and internal nuclear states, which provides the underlying interaction Hamiltonian for the many anomalies that have been reported over the years. This past year the group has made use of the interaction to develop a computation of phonon-nuclear coupling for the 6.237 keV nuclear transition in Ta-181. This transition is singular within the theory, since it is one of the very rare low-energy electric dipole transitions for stable nuclei—in fact, the lowest of them.

The group had proposed a Mossbauer experiment in the homonuclear diatomic molecule Ta2, in which phonon-mediated coupling leads to a small splitting of the excited nuclear and vibrational states. The thought was that this would provide an elegant way to observe the coupling in a conventional frozen argon matrix experiment. Now that we have an estimate for the coupling matrix element we are able to evaluate the splitting. Unfortunately the splitting consistent with our estimate is too small to be observed. We have been interested for many years in developing a basic understanding of the anomalies in order to develop an associated engineering discipline that can be used to develop new technologies. The identification and reduction of the phonon-nuclear interaction in our view constitutes a big step in this direction.

Experimenting to test phonon-nuclear coupling. Over the years there have been numerous claims of experiments showing unexpected anomalies of one sort or another in the field of condensed matter nuclear science, several of which permit an interpretation of nuclear excitation through the up-conversion of vibrations. We have been working toward the development of an experimental facility in which to test some of these claims, and also to test new experiments that have been proposed.

Some years ago we worked with SRI to see whether we might observe X-ray emission and charge emission from a copper foil vibrated around 20 MHz. The SRI team reported signals consistent with positive results for both effects, which was cause for some excitement. We found first that the calibration of the X-ray detector was off, and when corrected showed the X-ray measurements to be an artifact. Subsequently, we ran tests at MIT to see whether we could confirm the charge emission. We saw signals something like what was reported at SRI, but as an idiot check when we tried to charge a capacitor with the associated charge, we were unable to get a voltage. The charge emission signal in our experiment was an artifact. SRI carried out a similar test on their version of the experiment with similar results. We discussed in last year's report a confirmation test for Kornilova's waterjet experiment, in which collimated X-ray emission in the keV regime are claimed. In our tests we found several artifacts associated with pinholes and bent film, but no X-ray emission.

We began phonon-nuclear coupling experiments this spring. A test of up-conversion in a steel plate vibrated near 100 watts around 2.23 MHz showed a variety of artifacts, but in the end produced a negative result. We tried an excitation transfer experiment with a Co-57 source evaporated on a steel plate in which we looked for a reduction in source emission on the 14.4 keV transition during vibrational stimulation. In the course of the experiment we encountered a variety of artifacts, and ultimately there was no sign of an excitation transfer effect of the sort sought.

However, in the data there was evidence for non-exponential decay of the 14.4 keV gamma and also in the Fe $K\alpha$ and $K\beta$. Based on previous experience we suspected another artifact. However, in this case the detectors appear to have functioned properly. We were not able to reproduce the effect at the level first observed; however, we were able to develop a weaker version of the effect in response to different stresses applied to the sample. At this point we have seen non-exponential decay in six or seven runs, and have seen evidence for the anomaly on three different detectors.

What we see is an enhancement of the 14.4 keV gamma and the Fe $K\alpha$ and $K\beta$ X rays. We may also be seeing a reduction of emission of the 122 keV and 136 keV gammas, but we will need direct measurements to be sure. The enhanced emission on the surface seems qualitatively consistent with an up-conversion effect as described by the model that we are testing; however, since at times where the enhancement is evident there is no obvious source of high-frequency phonons to be up-converted, we have come to the conclusion that enhancement is not a result of the specific physics described by the model.

At present the physics community does not believe that phonon-nuclear coupling is possible, that up-conversion of the kind under study is possible, or that there can exist a stress-induced nuclear excitation effect. The experiments that we are pursuing have a real possibility of providing clarification as to the reality of the coupling, as well as providing a tool with which we might understand in detail the underlying mechanisms. At present we are working toward the development of protocols suitable for use by other researchers.

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 the highest operating temperature in the pulsed mode ~200 K (without a magnetic field) and 225 K (with a magnetic field) and the highest operating temperature in the CW mode (117 K). The group performed real-time Thz imaging at a video rate of ~20 frames per second. They 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). More recently, they developed the first THz laser frequency combs and demonstrated dual-comb spectroscopy. These experiments have the potential to lead to improvements in sensing, imaging, and high-bandwidth communications.

Professor John Joannopoulos and Professor Marin Soljačić work together as a team in the area of nanophotonics. They are enthusiastic about their recent work on electrons interacting with plasmonic structures, which can give rise to resonant excitations in localized plasmonic cavities and to collective excitations in periodic structures. They investigated the presence of resonant features and disorder in the conventional Smith-Purcell effect (electrons interacting with periodic structures) and observed the simultaneous excitation of both the plasmonic resonances and the collective excitations. For this purpose they introduced a new SEM-based setup that allows us to probe and directly image new features of electron-photon interactions in nanophotonic structures like plasmonic crystals with strong disorder. This work creates new possibilities for probing nanostructures with free electrons, with potential applications that include tunable sources of short-wavelength radiation and plasmonic-based particle accelerators. The results of this work appear in a paper published in *Physical Review X* in 2017.

Professor Steven Johnson leads the Nanostructures and Computation Group. His research focuses on two areas. The first is the influence of complex geometries, particularly in the nanoscale, on solutions of partial differential equations—especially for wave phenomena and electromagnetism, analytical theory, numerics, and design of devices and phenomena. The second area of research focuses on high-performance computation, such as fast Fourier transforms, solvers for numerical electromagnetism, and large-scale optimization.

One of the major thrusts of Professor Johnson's recent work has been to prove rigorous upper bounds on the efficiency of light–matter interactions and hence both limits and engineering targets for the maximum performance of optical devices. Last year, in collaboration with Professor Soljačić, the team demonstrated experimentally that silver nanodiscs could be fabricated and measured to nearly hit theoretical upper bounds (derived in the previous year) for scattering and absorption over the entire visible spectrum. When compared to nanoparticles previously used for this purpose (e.g., for smoke grenades), the silver nanoparticles are nearly an order of magnitude better (per weight). At a theoretical level, working with Professor Owen Miller (Yale University), the researchers extended the light–matter bounds to include two-dimensional materials such as graphene: given only the surface conductivity, they were able to prove the upper limit (for *any* shape) on per-area scattering, absorption, spontaneous emission, and other quantities. Computationally, they showed that the upper limits on scattering and absorption are achieved by simple ellipse-like graphene shapes.

Previous work on upper bounds to spontaneous emission (determined by the local density of states or LDOS) showed that conventional nanoparticle structures were orders of magnitude from hitting the theoretical upper bounds, suggesting enormous room for improvement via engineering design. One tantalizing route to improvement is to utilize exotic resonances called "exceptional points" that can occur when two resonant frequencies coincide. Traditional theoretical formulation of the Purcell enhancement for resonant LDOS fail spectacularly at exceptional points, naively yielding an infinite result, and no correct general theory was available. This spring, however, the group derived the first fully general theory of LDOS and spontaneous emission at exceptional resonances, showing that large but finite enhancements are possible (especially in the presence of gain). Furthermore, they developed new numerical and semianalytical techniques for analyzing lasing in complex structures for degenerate lasing resonances, leading to the first complete nonlinear models of degenerate photonic-crystal lasing modes.

Professor Franz Kaertner's research focuses on the study of attosecond science, both in the gas-phase and on electronic-photonic chips, single to sub-cycle pulse generation in the mid- to long wavelength infrared, 2–10 micron wavelength, via parametric amplification. Jointly with the Microphotonics Group of Michael Watts, the research attempts to integrate femtosecond laser technology on a CMOS-Chip in a fully 3D photonic-electronic integrated platform to enable advanced ultrafast optical signal synthesis and signal processing.

The Kaertner group has continued to investigate sub-cycle optical field emission from nanoplasmonic field emitter arrays fabricated by Professor Berggren's group. Detailed analysis and modeling of field emission has shown that the signature of strong field emission when transitioning from the multi-photon regime called channel closing can be observed in the emission currents from silicon nanotips. Nano-emitters can be used for ultrafast sampling of electromagnetic signals up to optical frequencies or as modulated electron beam source for future coherent X-ray sources.

Lead by Dr. Hong the group has further pushed sub-cycle pulse generation with carrier-envelope phase control in the 2–10 micron range using parametric amplification in novel nonlinear optical materials such as zinc-germanium-phosphate and cadmium-silicon-phosphate. Using those pulses, high harmonic generation (up to the 12th harmonic) has been observed, limited only by the available spectrometer. The group also used the short pulse 2-micron system to demonstrate waveform controlled high order harmonic generation in gases.

Together with the group of Michael Watts leading the AIM-effort, the group has fabricated a first complete femtosecond laser on a silicon photonics platform. They have observed stable mode-locking with about 200 fs pulses at 600 MHz repetition rate. The device showed two closely spaced output pulses. This demonstration was very important for the group in order to reach Phase II of the DARPA On-Chip Digital Optical Synthesizer Project. The team is now in a position to optimize this laser for current and future programs, enabling the use of ultrafast optical systems using short pulses for optical frequency combs, putting high-speed photonically assisted analog-to-digital convertors onto fingernail-sized chips fabricated by advanced microelectronic and photonic fabrication techniques.

Professor Leslie Kolodziejski is collaborating with Professors Michael Watts, Franz Kaertner, and Erich Ippen on creating an on-chip synthesizer. The group is working on a 1.9 µm mode-locked laser based on thulium-doped aluminum oxide ($Tm^{3+}:Al_2O_3$) gain medium that will be frequency broadened and doubled with integrated optical devices. In terms of material studies, after developing the deposition process for this gain medium, various spectroscopic parameters were characterized. Absorption cross-sections around the pump wavelengths of 790 nm and 1600 nm, and the spontaneous emission lifetime were measured. During this analysis, a general method was developed for investigating the pump power dependence of effective lifetime of a gain medium. The method was verified with fibers whose lifetimes are well known and used for determining the lifetime of the newly developed $Tm^{3+}:Al_2O_3$ waveguides. In order to route and manipulate the light emitted from the thulium lasers, the group is also working on various types of novel optical filters. As a part of this effort, the first optical short-pass/long-pass filter has been demonstrated. This transmissive dichroic filter can achieve extremely sharp roll-off behavior around the cutoff wavelength up to 100 times better than devices demonstrated before. As the optical analog of an RC low-pass filter commonly used in electronics, this integrated dichroic filter can be incorporated into many optical systems due to its scalability and ease of design. Many examples of reflectors, splitters, combiners such as pump couplers, broadband wavelength division multiplexing systems, or visible and infrared routing solutions can be realized the with the dichroic filters as a part of this effort. Some of these filters will be used in the integrated system that stabilizes various frequency components of the aforementioned on-chip mode-locked laser.

Professor Rajeev Ram and the Physical Optics and Electronics Group pursue investigations in two major thrusts: integrated photonics and electron transport in semiconductors. Current work is focused on unconventional classical and quantum computing CMOS; microsystems for the measurement and control of cellular metabolism; and thermodynamic limits of photonics.

Professor Ram and his team reported on a microbioreactor used to control synthetic gene networks engineered in yeast. The flexibility of this platform was demonstrated through the switchable production of two different therapeutic proteins (interferon and human growth hormone). The experiments were performed by Ningren Han in close collaboration with Pablo Perez-Pinera in Timothy Lu's group and reported in *Nature Communications*.

The first integrated photonic platform for trapped ion quantum computing was reported in Nature Nanotechnology. This is the first element of a scalable architecture for integrated trapped ion quantum computing developed by Karan Mehta.

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 optical communications, optical phased arrays, optical beam-steering, low-phase noise optical-microwave oscillators, and microwave signal generation. Professor Watts's group has demonstrated the largest optical phased array ever produced, at 4,096 elements, projecting the MIT logo in the far-field, published in *Nature*, January 10, 2013. Building on this demonstration, Professor Watts has applied these results to the application of chip-based LIDAR, achieving the largest scan angle of any chip-based optical phased array at 51°. While separately demonstrating chip-based LIDAR with millimeter-scale resolution as well as chip-based heterodyne interferometry with nanometer-scale resolution, technologies poised to impact automotive accident avoidance/autonomous vehicles and precision metrology, respectively. Additionally, Watts's group demonstrated a new record in low-power silicon modulators, achieving <1fJ/bit in modulators running at 25Gb/s in the world's first 300 mm silicon photonics platform in collaboration with the College of Nanoscale Science and Engineering (CNSE) in Albany, New York. Additionally, combining the ultralow power silicon modulators with 3-D wafer CMOS integration, Professor Watts's group demonstrated the world's lowest power communication link at just 250fJ/bit, results that are sure to impact low power communication links in future high-performance data centers. Together, these results and the platform built between Watts's group and CNSE led to the recently announced win of the Photonics IMI, an effort with a total anticipated funding level of over $600 million.

Principal research scientist Kyung-Han Hong has been leading the development and application of the novel, strong-field ultrafast lasers in the Optics and Quantum Electronics Group. Hong's accomplishments span a range of topics in ultrafast laser sciences and strong-field laser physics. His research has focused primarily on ultrashort pulse amplification and ultrafast nonlinear optics in the infrared and terahertz range and secondly its application to strong-field, laser-matter interactions such as soft X-ray high-order harmonic generation (HHG), attosecond (10_{-18} s) science, and electron acceleration. The most recent work includes the coherent synthesis of mid-infrared (mid-IR) subcycle pulses, HHG in solids toward petahertz electronics, and the enhanced soft X-ray HHG using two-color mid-IR laser pulses. Hong made a progress in three subareas during the period of July 1, 2016 through June 30, 2017.

Mid-IR subcycle pulse synthesis. Hong's group demonstrated and fully characterized a phase-stable subcycle coherent pulse synthesizer covering the spectral range from 2.5 to 9.0 μm based on an optical parametric amplifier in a $CdSiP_2$ crystal. We measured the synthesized pulse duration of ~12.4 fs at ~4.2 μm, corresponding to <0.9 optical cycle. The energy of synthesized subcycle pulse is record-high ~33 μJ with multi-GW peak power. This is the first demonstration of energy-scalable subcycle pulse generation in the mid-IR.

HHG in solids toward PHz electronics. With mid-IR-driven HHG in solids one can study and control the subcycle dynamics of electrons in solid-state materials, opening up a whole new research field—so-called solid-state attosecond science, or petahertz (10_{15} Hz) and sub-petahertz electronics. Using the mid-IR pulse synthesizer described above, the team demonstrated HHG in solids (silicon, NiO, ZnO, and diamond). Especially from thin silicon samples (200- and 500-nm thick) we observed HHG up to the 19th order using few-cycle mid-IR pulses centered at ~4.2 μm. Both even and odd harmonics were observed due to the symmetry-broken electric field generated by mixing ~3.2 μm signal and ~6.5 μm idler pulses. Finally, using the synthesized subcycle mid-IR pulses, we were able to observe continuous harmonic spectrum for the first time, indicating the single harmonic emission and isolated electron dynamics in solids.

Two-color (ω+3ω) driven HHG with enhanced efficiency. The subcycle control of electrons in soft X-ray HHG in gases for efficiency enhancement was demonstrated with two-color mixing of drive pulses. The group experimentally studied HHG using optimal waveforms, which have been theoretically predicted by our collaborators at Kansas State University (KSU). In this experiment, we mixed a mid-IR (2.1 μm, ω) pulse and its third-harmonic (3ω) with 10% of ω energy and tuned the relative delay (or phase) with subcycle resolution while running HHG in Ar. An efficiency enhancement of up to >8 times was observed in low, 20-70 eV, photon energy while no enhancement, at >140 eV. Extensive simulations by the KSU collaborators show relatively good agreements with experimental observations.

Quantum Computation and Communication

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

Professor Paola Cappellaro's Quantum Engineering Group has devised several strategies to improve quantum sensors using spin defects in diamond. Efforts have included improving the sensor coherent lifetime to achieve longer measurement times and higher sensitivity, as well as using a larger number of entangled sensors. The first direction focused on improving the coherence time of the nuclear spin associated with the spin defect using two strategies. On one side, novel control techniques are used to protect the nuclear spin from noise; on the other side, a nearby electronic spin defect is used to sense external noise variations and feedback control is applied on the nuclear spin to stabilize it. To improve sensitivity by using more than one spin sensor, the group has developed control techniques to address a small network of spin defects, entangle them, and use them for sensing. This approach promises to achieve sensitivities beyond what is possible for classical sensors. Professor Cappellaro's group also achieved the first measurement of many-body localization in a natural nuclear-spin system. While it is known that a quantum system will localize in the presence of disorder, whether this localization (which prevents, for example, thermalization) survives in the presence of interactions (many-body localization) is still an open question. By combining Hamiltonian engineering techniques, analytical models, and detection of spin-spin correlations via NMR techniques, the group was able to experimentally measure the characteristic logarithmic growth of correlation linked to many-body localization.

Professor Isaac Chuang's group studies theoretical and experimental quantum information science, and seeks to harness the laws of quantum physics to solve hard problems faster than is possible with conventional classical computers. In 2017, his group developed a novel quantum signal-processing algorithm for quantum Hamiltonian simulation, obtaining a run time that is linear in time and logarithmic in the bits of precision desired using standard Hamiltonian queries. This saturates the lower bound, and presently holds the record for the best such quantum simulation algorithm. It was made possible through incorporation of ideas from discrete time signal processing, and is an example of a general composite quantum gates methodology. These discoveries have been reported in *Physical Review X*, *Physical Review Letters*, and the Quantum Information Science conference, the premiere meeting of the quantum computing community. We also collaborated with the Chiaverini-Sage trapped ion quantum computing group at MIT's Lincoln Laboratory to realize the first ever experimental demonstration of quantum enhanced imaging, locating the position of an object with uncertainty scaling as 1/t, which is far superior to the usual short-noise limit of 1/sqrt(t).

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

Any implementation of a quantum computer requires individual qubits with long coherence times and fast, high-fidelity control. In superconducting systems, most quantum circuits are realized using transmon qubits, which are weakly anharmonic LC-oscillators. Although transmon qubits generally have good coherence times and are relatively straightforward to fabricate, the existence of higher excited states in these systems makes it difficult to apply fast and accurate qubit control pulses without leaving the computational subspace spanned by the two lowest energy levels. To reduce such state leakage, the group has developed a new qubit that combines the best of properties of the transmon, namely its insensitivity to charge fluctuations, and the flux qubit, which has a much larger anharmonicity, giving qubits states that are better isolated from higher levels in the system. With this new device, the capacitively-shunted flux qubit, the group has demonstrated state-of-the-art coherence times ($T_1 > 50$ μs, $T_2^{Echo} > 90$ μs) with twice the anharmonicity of the transmon qubit. The work was published in Nature Communications in 2016.

During the past year, the group completed experiments and wrote a paper on stochastic pumping techniques for improving qubit energy relaxation. The work was published in *Science* in 2016. Dynamical error suppression techniques are commonly used to improve coherence in quantum systems. They reduce dephasing errors by applying control pulses designed to reverse erroneous coherent evolution driven by environmental noise. However, such methods cannot correct for irreversible processes such as energy relaxation. Instead, we investigated a complementary, stochastic approach to reducing errors: instead of deterministically reversing the unwanted qubit evolution, we used control pulses to shape the noise environment dynamically. In the context of superconducting qubits, we implemented a pumping sequence to reduce the number of unpaired electrons (quasiparticles) in close proximity to the device. We applied the technique to several flux qubits, and found a 70% reduction in the quasiparticle density, resulting in a three-fold enhancement in qubit relaxation times, and a comparable reduction in coherence variability.

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

Professor Jeffrey H. Shapiro and Senior Research Scientist Franco N. C. Wong have been working on theory and experiments related to reaching ultimate quantum limits in communication, imaging, and precision measurements at optical frequencies, where quantum noise is often dominant and conventional techniques are known not to reach ultimate performance limits. This year the group has made several significant achievements. They have continued their development of floodlight quantum key distribution (FL-QKD), a novel method for securely distributing encryption keys that overcomes channel loss to potentially achieve a gigabit per second key generation rate that is suitable for practical encryption of large files. In particular, the group has upgraded the experimental setup and is now getting preliminary results that demonstrate FL-QKD operation at gigabit per second secret-key rates. This demonstration is being made in a tabletop experiment that employs channel attenuation equivalent to a 50-km-long optical fiber connection, but the group is exploring the possibility of performing future experiments on the 40 km optical fibers that link the MIT campus with Lincoln Laboratory.

A second area in which the Shapiro-Wong group has scored an important achievement this year was the demonstration of the highest-purity generation of spectrally unentangled biphotons. The signal and idler photons that comprise such biphotons are each in well-defined spatiotemporal modes, making them ideal for a wide variety of quantum information processing tasks. As reported in *Optics Express*, the biphotons had an unprecedented 99% purity. They were generated by spontaneous parametric down-conversion (SPDC) in a periodically poled $KTiOPO_4$ crystal that was designed to have a Gaussian-shaped phase-matching function. This new characterization employed a novel means to obtain their joint spectral intensity, and this new measurement technique, which relies on frequency-to-time encoding using dispersion-compensation modules, is far more sensitive and efficient than prior approaches to biphoton characterization.

A third achievement came from the group's continuing theoretical work on quantum-illumination (QI) target detection, an entanglement-based scheme that enables laser or microwave radars to outperform classical systems of the same transmitted energy in detecting the presence of a weakly-reflecting target that is embedded in strong background noise. In a paper published in *Physical Review Letters*, the team described and analyzed the first structured receiver capable of realizing the full performance gain afforded by QI. In a subsequent *Journal of the Optical Society of America B* paper, the lab then reported the first receiver operating characteristic (ROC) analysis—detection versus false-alarm probability tradeoff—for QI target detection. All previous QI performance analyses had used error probability, calculated under the assumption that target absence or presence were equally likely, whereas the ROC is the preferred performance metric for laser and microwave radar owing to the difficulty of assigning accurate prior probabilities, and the vastly unequal consequences of a false-alarm error versus a missed-target error.

Finally, in another *Physical Review Letters* publication, the group borrowed the concept of amplitude amplification from quantum computation's famous Grover search algorithm and combined it with the fully-quantum theory of SPDC to show how paired n-photon states of signal and idler light could be generated from an *n*-photon pump beam with unity efficiency. This work has already attracted interest from leading experimental groups, owing to its potential applications in quantum metrology, quantum cryptography, and quantum computation.

Personnel

Professor Polina Anikeeva was promoted to associate professor with tenure on May 5, 2017 and was appointed to associate director of the Research Laboratory of Electronics in January 2017. She is the first woman to hold this position in the laboratory.

Professor Marc Baldo was appointed as interim Director in the Research Laboratory of Electronics in August 2016 and as director of RLE in January 2017.

Professor Paola Cappellaro was promoted to associate professor with tenure in July 2016.

Professor Thomas Heldt was appointed the W. M. Keck Career Development Chair in Biomedical Engineering at MIT. He was also promoted to the rank of associate professor without tenure in the Department of Electrical Engineering and Computer Science.

Professor Timothy Lu was promoted to associate professor with tenure in May 2017.

Professor William Oliver was jointly appointed Lincoln Laboratory Fellow and associate director of RLE in January 2017.

RLE Headquarters had five hires this year, Richard Petruzzelli (assistant director for Administration), Benjamin Sharma (financial assistant II), David Barnett (fiscal officer), Andrew Iannaccone (fiscal officer), and Thao Phan (fiscal officer). Catherine Bourgeois was promoted to program manager and assistant to the director, Marybeth Corcoran was promoted to fiscal officer, Maxine Samuels was promoted to Human Resources coordinator, and Fionnuala Coary was promoted to financial coordinator. Mary Markel Murphy (assistant director for Administration and Human Resources) left RLE to become assistant dean of Administration and Human Resources at the School of Engineering. Joseph Foley (fiscal officer) left RLE to join the Office of Sponsored Programs as a cost analyst. Cathy Borgesen (fiscal officer) left RLE to join the Office of the Provost as assistant director of Research Development. Cherry Mui (fiscal officer) left RLE to join the MIT Energy Initiative as a fiscal officer. Cheryl Charles (fiscal officer) retired. Hien Nguyen (administrative assistant II) left RLE to relocate to North Carolina and is pursuing her career at Duke University. Thao Phan (fiscal officer) left RLE to pursue her education full-time.

The RLE community lost two respected and beloved members this year.

Millie Dresselhaus, PhD ’58, Institute Professor emerita of Electrical Engineering and Computer Science and of Physics, died on Monday, February 20, 2017, at the age of 86. Dresselhaus’s research helped unlock the mysteries of carbon. Dresselhaus became the first woman at MIT to attain the rank of full, tenured professor. Among her many awards and honors, Dresselhaus was the first woman to win the National Medal of Science in Engineering. She also won the Presidential Medal of Freedom and the National Medal of Science. She was well known for her work in carbon-based nanotechnology and was unparalleled as a gifted mentor. An obituary written by the MIT News Office can be found on their website.

Nathaniel I. Durlach ’54, joined the Research Laboratory of Electronics in 1963 and served as a senior lecturer. He passed away at home in the company of his family on Tuesday, September 27, 2016. He was 88. Durlach was a devoted researcher, and author or co-author of approximately 100 journal articles. He was an active reviewer of articles for professional journals (e.g., *Science*, *Journal of the Acoustical Society of America*, *Hearing Research*, *Perception*, and *Psychophysics*) and of proposals for governmental funding agencies (e.g., National Science Foundation, Air Force Office of Scientific Research). Durlach was a recipient of the Silver Medal award from the Acoustical Society of America, was the chair of the committee formed by the National Academy of Sciences to establish a national agenda for research and development on teleoperator and virtual environment systems, and had been both a director of and consultant to a number of technology companies concerned with measurement, enhancement, or both, of human sensorimotor performance. He was known for his enthusiasm, intellectual honesty, and ability to spark creativity among his colleagues.

Faculty Honors and Awards

Professor Polina Anikeeva received the NIH Brain Initiative grant in October 2016.

Professor James Fujimoto was the recipient of three awards in 2017. He was co-recipient of the National Academy of Engineering Russ Prize along with Eric Swanson (MIT), and Professor Christoph Hitzenberger and Adolf Fercher (Medical University of Vienna)—for optical coherence tomography, leveraging creative engineering to invent imaging technology essential for preventing blindness and treating vascular and other diseases. The Russ Prize is a $500,000 prize awarded biannually and recognizes an outstanding bioengineering achievement in widespread use that improves the human condition.

Professor Fujimoto was co-recipient of the European Inventor Award in the non-EPO category along with Eric Swanson (MIT) and Professor Robert Huber (Universität zu Lübeck). The award is selected by a jury based not only on technological originality but also on economic and social impact.

Fujimoto received the Beckman-Argyros Award in Vision Research, a $500,000 award to one individual annually who has made and is continuing to make significant transformative breakthroughs in vision research, particularly through the development of an innovative technology or fundamental scientific breakthrough that has been applied to and improved the vision sciences.

Professor Leslie Kolodziejski was presented the Faculty Ambassador Award at the Multicultural Awards Banquet of the Institute Community and Equity Office.

Professor Muriel Médard received the IEEE Information Theory Society Aaron D. Wyner Distinguished Service Award in 2017.

Professor Rajeev Ram was elected an Optical Society of America Fellow in 2014. In 2015, Professor Ram was named a Bose Research Fellow. He was elected as an IEEE Fellow in 2016.

Henry I. Smith, professor emeritus of electrical engineering, was awarded the 2017 IEEE Robert Noyce Medal.

Professor Yang Shao-Horn was elected an Electrochemical Society Fellow in 2017. She also received the Electrochemical Society Battery Research Award in 2016.

Professor Lizhong Zheng was elected as an IEEE Fellow in 2017.

Professor Martin Zwierlein was elected as an American Physical Society Fellow in 2016 and was awarded the I. I. Rabi Prize with the American Physical Society in 2017.

Staff Awards

The following RLE community members won the 2017 Infinite Mile Award under the Office of the Vice President for Research: William Adams, RLE's systems infrastructure administrator in IT administration; and Josephina Lee, administrative assistant for Professors Jeffrey Shapiro, Terry Orlando, Clifton Fonstad, Cardinal Warde, and Peter Dedon.

Student Awards

The 2016 Helen Carr Peake Research Prizes were awarded in September of 2017 to Fahim Farzadfard, a doctoral student in Biology, and Sarvesh Varma, a doctoral student in Electrical Engineering and Computer Science. Farzadfard's research is supervised by Timothy Lu. Farzadfard ws recognized this year for his demonstrations of novel schemes for biological computation. Sarvesh Varma's research was supervised by Joel Voldman, professor of electrical engineering and computer science. Varma is recognized this year for his contributions to the microfluidic biosensor technology.

The 2017–2018 Claude E. Shannon Research Assistantship was awarded to Yuezhen Niu, doctoral student in the Physics Department. Niu's doctoral research is co-supervised by Ike Chuang, professor of physics and of electrical engineering and leader of RLE's Quanta Group; and Jeffrey Shapiro, the Julius A. Stratton Professor of Electrical Engineering and leader of RLE's Optical and Quantum Communications Group. Niu is recognized this year for her significant accomplishments and outstanding promise in the rapidly developing intersection of photonic quantum computation, quantum error correction, and nonlinear quantum optics. Niu is most deserving of this prestigious award.

Affirmative Action and Outreach Activities

RLE continues working to increase the number of women and minorities in career positions in the laboratory. This year we welcomed Professor Polina Anikeeva as an associate director of the lab. We are also pleased that Professor Farnaz Niroui will be joining us as junior faculty in 2018. Finally, we have made arrangements to host Anita Hill, a law professor from Brandeis University, on her sabbatical at MIT as a Martin Luther King Jr. scholar. She will be conducting research on Title IX and its role in science and technology education together with Muriel Médard of the Network Coding and Reliable Communications Group. Professor Hill's visit will coincide with the rollout of Title IX training within RLE. We expect that Hill and Médard's plan for a series of open lectures by prominent scholars will raise the profile of Title IX issues within the laboratory and the Institute as a whole.

Additional specific measures include maintaining our high standards for recruitment procedures, among them sending job postings to professional organizations for professionals of color, working closely with the RLE faculty and staff supervisor at the beginning of each search to identify ways of recruiting minority and women candidates, and being committed to finding new techniques to identify women and minority candidates more effectively. During the past year, RLE appointed one woman, and promoted two women to exempt-level staff positions in headquarters.

RLE has continued its work in nurturing future generations of engineers and scientists. Again this year, the Center for Ultracold Atoms (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 is the experience of actual teaching. The two teams of students worked under the direction of a master teacher to prepare and teach students at the middle school and high school levels. Middle and high school students were recruited largely from local schools, with some traveling from other states to take part. This was the 13th year in which CUA ran the program.

The laboratory is extremely grateful for the profound dedication of its principal investigators—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.

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