Research Laboratory of Electronics

The Research Laboratory of Electronics (RLE) at MIT is a vibrant intellectual community and one of the Institute's earliest interdepartmental academic research centers. Research at RLE 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 laboratory's research runs from the fundamentals of quantum physics and information theory to synthetic biology and power electronics. RLE's work extends to novel engineering applications, ranging from those that produce significant advances in communication systems or enable remote sensing from aircraft and spacecraft, to the development of new biomaterials and innovations in diagnostics and treatment of human diseases.

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

With a research volume of $50.1 million in fiscal year 2018, RLE continued to be one of the Institute's principal research organizations. The laboratory manages more than 200 active research projects and services for more than 70 principal investigators. In fiscal year 2018, RLE included approximately 250 graduate students and more than 70 undergraduates.

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

Laboratories and Research Highlights

Academic year 2018 saw many awards, recognitions, and milestones for RLE investigators. A summary follows.

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.

Ultracold molecules with permanent electric dipole moments have gained considerable attention in recent years as promising new systems to study quantum chemistry and quantum many-body physics. An additional magnetic dipole moment provides an extra degree of control that can be used for magnetic trapping, tuning collisions and chemical reactions, simulation of spin-lattice Hamiltonians, or, as in the case of cold magnetic atoms, the direct study of magnetic dipole interaction effects.

Professor Wolfgang Ketterle's research group is using ultracold atoms to explore new forms of matter at temperatures close to absolute zero. Members of Professor Ketterle's laboratory created fermionic dipolar molecules of the isotope of sodium with atomic mass 23 (^{23}Na) and the isotope of lithium with atomic mass 6 (^{6}Li) (^{23}Na^{6}Li) in their triplet ground state from an ultracold mixture of ^{23}Na and ^{6}Li. Using magnetoassociation across a narrow Feshbach resonance, followed by a two-photon stimulated Raman adiabatic passage to the triplet ground state, 3×10^4 ground state molecules in a spin-polarized state were produced. Researchers observed a lifetime of 4.6 seconds in an isolated molecular sample, approaching the p-wave universal rate limit. This is a 10,000-fold improvement on previous triplet lifetimes in ultracold dipolar molecules. Electron spin resonance spectroscopy of the triplet state was used to determine the hyperfine structure of this previously unobserved molecular state.

The research of Professor Vladan Vuletic focuses on large quantum mechanical systems and on how quantum correlations (entanglement) can be used to perform tasks that are impossible within classical physics. A particular focus is on how to use quantum correlations (entanglement), which are stronger than classical correlations, to improve atomic clocks and atomic interferometers and to control photons individually. Recent research highlights by the Vuletic group included the first observation of a molecule of light comprising three photons, the demonstration of a quantum simulator with 51 individually controllable interacting atoms, the observation of strong entanglement in an atomic clock, and the production of Bose-Einstein condensates in record time by laser cooling.

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

The outstanding highlight of the Zwierlein laboratory's research over the past year was the observation of spin transport in a Fermi Mott insulator. This state is insulating, not because there is no more space in the energy band, but because of interactions between particles. The experiment was a pristine realization of the Fermi-Hubbard model, believed to hold the key to the understanding of high-temperature cuprate superconductors. However, this model cannot be simulated on a classical computer. Transport coefficients are basically impossible to obtain theoretically with any satisfying accuracy. In the experiment in the Zwierlein laboratory, researchers directly observed the transport of fermions with single-atom resolution and obtained precise values for such transport coefficients. In particular, understanding the motion of spins is crucial, as it is conjectured that it is the condensation of spin singlets that leads to superconductivity. This work demonstrated that at least two mechanisms are responsible for spin transport—so-called superexchange processes, where spin-up and spin-down particles trade places, and direct tunneling of spins assisted by fluctuations that leave an empty site available to move through.

Researchers were also able to study sound attenuation and viscosity in a strongly interacting Fermi gas. This form of matter acts as a perfect liquid, the only other example of which is the quark–gluon plasma that existed a split second after the Big Bang. Sound attenuation in the experiment's Fermi gas was shown to occur at a quantum limited rate, described by a sound diffusivity on the order of Planck's quantum divided by the particle mass (around 10^{-8} meters squared per second). This has strong analogies with another strongly interacting quantum liquid, helium-4, where the kinematic viscosity also attains this quantum limit.

Experiments on strongly interacting fermions indicated that research on ultracold atoms is entering an era where measurement outcomes can no longer be predicted by theory—where a true analog quantum computation takes place. The hope is that theoretical methods can be "trained" on these experimental results so that they can be used to predict the behavior of other fermionic systems in nature, such as strongly interacting electrons in modern materials.

Energy, Power, and Electromagnetics

This research theme comprises work in excitonics, studies in the absorption and emission of light, solar cells, disordered and low-dimensional materials, and complex nanostructures. It includes work on organic light-emitting diodes (OLEDs), nanowires, hybrid organic-inorganic materials, and organic structures and devices. More, it also covers 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 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 MIT's Department of Mechanical Engineering, members of Kirtley's group developed systematic methods for assessing and ensuring the 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. In the past year, Lyapunov methods were employed to generate "guarantees" of stability for these inverters. Although the criteria for stability were very conservative, they can serve as a rough guide when considering installing inverters.

The work on microgrid stability will continue under a new project with the Masdar Institute, now part of Khalifa University. The focus of that project is space systems and involves four faculty members at Khalifa (Hatem Zeineldin, Mohamed Shawky el Moursi, Vinod Khadkikar, and Mohamed Al Hosani) and three faculty members at MIT (Steven B. Leeb, David J. Perreault, and James Kirtley). A three-inverter microgrid is being assembled, along with one Typhoon motion simulator.

A project to design improved drive motors for battery-powered electric vehicles was begun in academic year 2018 with support from Magna International. Kirtley's group, consisting of postdoctoral associate Ho Tin Lee and two graduate students, considered a flux switching motor, two types of surface-mounted permanent magnet motors, and two types of induction machines. The MIT group designed some motors that appear to be very competitive with machines that are on the market or about to be on the market. Prototypes are being built and will be tested over the next several months. Efficiency was evaluated over a complete drive cycle. In a somewhat unexpected result, it was found that, for typical drive cycles, it is possible to do a good representation of the motor for efficiency determination with only about eight representative points (as opposed to about 1,800 for a typical drive cycle).

In collaboration with Fudan University in Shanghai, Kirtley's group started investigating motors for robots. One motor design under consideration is a combination of a motor and a magnetic gear. Mohammad Qasim, a member of Kirtley's group, began collaborating with Professor Vivek Agarwal of the Indian Institute of Technology, Bombay, in trying to design more efficient single-phase motors with higher power factors for applications such as appliances, pumps and, perhaps most important, ceiling fans. A specialized dynamometer was set up to measure the performance of ceiling fans. A project sponsored by the Tata Center at MIT is concerned with storage batteries used in direct current microgrids in remote areas. These are typically lead-acid batteries that have had poor service life in the past. The objective of the project is to understand why batteries are failing and to devise guidelines for operating them so as to have longer service lifetimes.

A second battery-related project was started with the sponsorship of the Office of Naval Research. William A. Lynch, research specialist in RLE, developed an experimental setup and is putting lithium ion cells through various use exercises to understand their dynamic performance. The goal is to enhance the use of such cells for pulsed power application on US Navy ships.

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

- Received US Patent 9,786,423 for a new magnetic field winding for concentrating magnetic field on a single side of a wire sheet. This approach, and the associated power electronics, greatly improves the power delivery efficacy for induction heating and charging applications.

- Received US Patent 9,945,692 for new methods for noncontact sensing for nonintrusive utility monitoring. Among other techniques, a new noncontact retrofit sensor was developed that permits a conventional in-home water meter to function as a high-accuracy flow meter suitable for nonintrusive fluid monitoring.
- Secured $5 million for the construction of a new electronics prototyping laboratory in RLE.
- Completed supervision and leadership of the renovation of the Grainger Energy Machines facility, a $4 million renovation project.
- Developed new mathematical techniques and circuits for noncontact power monitoring. These techniques permit the installation of monitors on a power grid without requiring a local calibration. Instead, meters can be installed anywhere using data from other convenient places on the utility to calibrate. These new techniques expand the applicability of nonintrusive power monitoring for condition-based diagnostics on critical platforms such as warships and oil rigs, where no interference with the power system can be tolerated.
- Developed a new technique for detecting instability on direct current microgrids and new power electronic control technologies for automatically remediating or avoiding instabilities.

Professor Jeffrey Lang's research generally focuses on the analysis, design, and control of electromechanical energy conversion and motion control systems. Its applications involve high-performance electrical machine systems, micro- and nanoscale electromechanical actuators and sensors, or distributed electromechanical structures. Two illustrative examples of this research taken from the past year in the area of kinetic energy harvesting follow.

Energy harvesting is a process by which energy is extracted from the environment and converted to electrical energy for general purpose use. Hydropower, solar power, and wind power sources are common examples of large-scale energy harvesting. Kinetic energy harvesting (harvesting energy from vibrations and other motions in the environment) is an example of small-scale energy harvesting that could power remote sensor nodes and "internet of things" (IoT) devices. Over the past year, researchers made several important advances in such kinetic energy harvesting. Two are described below.

The first advance concerns vibration energy harvesting. Researchers developed an energy harvester, comprising a magnetic-based microelectromechanical (MEM) energy converter and its associated power and control electronics; these are fully fabricated in silicon, thereby permitting batch commercial fabrication. Operating with vibrations of 1.1 g at the nominal frequency of 76 hertz (Hz), the converter produces 2.2 milliwatts (mW) of power. The corresponding power density and normalized power density are 1.2 mW per cubic centimeter (cm^3) and 1.0 $mW/cm^3/g^2$, respectively; these densities are among the highest among silicon-based MEM converters reported to date. At the same time, the efficiency of the power and control electronics approaches 70%, yielding a near–1.5 mW overall power output. Perhaps more important, the harvester can cold-start and operate over a frequency range that is ±5% off nominal to offset variations in vibration spectra or MEM fabrication. This is a unique broadband accomplishment.

The second advance concerns acoustic energy harvesting. Ordinarily, acoustic waves do not offer much energy to harvest, but the application of interest was airports, which host significant amounts of aircraft noise. Researchers were also curious to understand the limits on acoustic energy harvesting in such environments. Acoustic energy at airports, created predominantly by aircraft during takeoffs and landings, is very broadly distributed, from approximately 50 Hz to 2 kilohertz (kHz). To harvest acoustic energy over this bandwidth requires an energy converter quite different from the near-single-frequency converters commonly used for kinetic energy harvesting. Further, a large collection area is desirable to intercept the greatest possible acoustic energy. Members of Lang's laboratory developed an energy converter based on a thin piezoelectric film that offered a 10-centimeter-square aperture with a low mass. Under proper control, such a device was able to harvest 2.3 microjoules (μJ) per takeoff or landing event at a distance of more than 1,000 feet. This is enough energy to record and evaluate the noise level and to send that information over a wireless sensor network back to a central station. Thus, the monitoring and evaluation of acoustic noise at an airport and in nearby neighborhoods could be powered by the acoustic noise itself.

Professor David Perreault's research has focused on advancing power electronics technology and in the use of power electronics to benefit key applications. Major research thrusts include the development of extreme high-frequency power conversion to attain miniaturization and integration, the development of power converters having greatly improved efficiency and operating range, and in the use of power electronics to benefits applications such as grid-interface power supplies, renewable energy systems, industrial processes, and aerospace systems. One valuable recent result has been the development and application of new hybrid magnetic/electronic components that can effectively provide high-frequency power transformers with fractional effective turns. This approach, the variable inverter rectifier transformer, offers a means to improve the loss in high-frequency power transformers while providing efficient power conversion over increased voltage and power ranges. Researchers are applying this approach to advance multiple applications, including wide output range grid-interface alternating current to direct current power supplies and direct current to direct current power converters for electric vehicles.

Professor David L. 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 past year, Professor Trumper and his group worked on six major projects.

- His group has been continuing to study the design of high-force and novel magnetically levitated linear motors for rapid and precise positioning in applications such as semiconductor manufacturing, with experimentally proven performance exceeding any commercially available linear motor. His group is also working on the design of a new type of hysteresis linear motor for reticle transport in a vacuum.

- In a collaboration with Professor Linda G. Griffith of the Department of Biological Engineering, Professor Trumper has been designing mechatronic solutions for novel multi-organ human tissue bioreactors. This research is creating new microphysiological systems for the in vitro study of human organ tissues such as brain, gut, and liver cells. Researchers are working toward a demonstration of new results for brain–gut–liver interactions in fall 2018.

- In another collaboration with Professor Linda Griffith and with Professor Rebecca Carrier of Northeastern University, Trumper's group is designing mechatronic solutions for microphysiological systems for studying human gut behavior in the presence of gut bacteria, as well as gut–liver interactions. As part of this effort, his group has designed new types of platform mechatronic flow configurations and new electromagnetic actuators for highly power-efficient microfluidic pumping.

- Professor Trumper is also working with an industrial partner to design new types of magnetically levitated impellers for blood oxygenation pumping. These novel pumps have now experimentally demonstrated levitation and control of pumping rotation. They have also been successfully used for bench-level pumping of blood with acceptable results, which makes possible the next steps of testing on animal subjects. Laboratory members plan to work with the industrial partner to apply for funding to support a Small Business Technology Transfer Phase II effort toward creating a working product for human use, with a focus on pediatric patients.

- In a completed collaboration with the Masdar Institute, Professor Trumper's group designed new approaches for solar energy collection and storage in a molten salt system. Several papers have been submitted to conferences and journals on this topic.

- In a collaboration with MIT's Lincoln Laboratory, Professor Trumper's group is designing a new type of momentum wheel for microsatellite attitude control. This design has successfully demonstrated one-axis levitation and is being configured for full three-axis levitation and three-axis angular momentum control, with experimental demonstration expected in the next few months. Laboratory members are also working with Lincoln Laboratory to secure funding for the design and testing of a flight-qualified unit.

Principal Research Engineer Chathan M. Cooke is a member of LEES. His work is mainly directed to three areas: resonant magnetic power transfer, magnetic induction undersea communications, and energetic electron/photon beam interactions.

For the work on resonant magnetic power transfer, Cooke and Electrical Engineering and Computer Science (EECS) graduate students Angel Carvajal and Daniel Ervin Schemmel combined detailed modeling and experiments to develop a complete "wire to performance" simulation model. The model will make it possible to determine performance efficiency accurately for a given set of windings and their configuration. The primary application, for improved electronic transformers, is supported by industrial sponsor Prolec-GE. The modeling includes losses caused by skin and proximity effects and has been validated for frequencies to 200 kHz. The models and experiments indicated that high power transfer efficiencies of more than 95% can be achieved.

The Trumper group's magnetic induction communications work has been performed in collaboration with the MIT Sea Grant Program. With EECS graduate student Aaron S. Rose, the research has developed broadband magnetic sensing and magnetic induction transmitter coils. The goal here is to enable undersea communications to transmit data from underwater sensors to an autonomous surface vehicle. Laboratory tank tests to calibrate the sensors range from 500 Hz to 1 megahertz (MHz). One planned example of the developed technology is to implement an array of permanently anchored temperature and salinity sensors to monitor ocean conditions near commercial fishing grounds to understand better the impact of ocean warming.

For energetic radiation work, electron and photon beams are produced by the Van de Graaff accelerator facility in Building N10, the High Voltage Research Laboratory. These beams have been applied to develop improved durability of materials for hip and knee implants, working with the Harris Orthopaedic Biomechanics and Biomaterials Laboratory at Massachusetts General Hospital. The beam has also been applied to basic physics studies performed by Professor Richard G. Milner and his graduate student Charles S. Epstein, who were the first to quantify the Møller effect at lower energies (below 10 megaelectronvolts) (MeV). The beam has been used to calibrate various satellite solar flux detectors made by satellite instrument companies. Energetic electrons have also been implanted into insulators as an effective means to quantify charge transport processes.

The resonant magnetic power transfer work offers an opportunity to devise new means to transfer energy from different types of sources, such as photovoltaic power and wind power, to the traditional power grid. This work employs first principles to achieve high efficiency and provides a great example of how basic electromagnetic principles can be applied to yield improved practical devices.

The ability to communicate over moderate distances, about one kilometer, is useful for modern sensing and opens the way for a new understanding of ocean dynamics, especially as ocean temperatures change fishing patterns. It also may become valuable for diver safety as a reliable means to communicate with the surface.

The biomaterials work offers the opportunity for very durable, long-life implants, such as prosthetic hip joints. This work with radiation-enhanced materials started at MIT; it is already a common technique used worldwide to enhance joint implant performance. The possibility of extending these surgically implanted materials to injectable form would reduce the cost and hazards associated with full surgical implants. The basic electron particle physics work is also very exciting, as it reveals a new understanding of the interaction among energetic particles.

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 biological microelectromechanical (bioMEMS) devices, 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 W. S. Chan's group focuses on ultra-high-speed and high-quality service guaranteed heterogeneous networks and their particular relevance to defense networks and cybersecurity. Their work includes applications over satellite, wireless, and optical communications and heterogeneous data networks. The objective is to develop the scientific base needed to design data communication networks that are efficient, robust, and architecturally clean, as well as study application scenarios and their modeling to enable research and development of the right network architecture. Their research this year had two main foci: cognitive optical networks and the internet of things.

Cognitive Optical Network Management and Control

In academic year 2018, Professor Chan's group started a new program funded by the NSF on cognitive optical networks. The optical network of the future (in five to 10 years) will see an increase of three to four orders of magnitude in data rates. To keep the cost affordable, an agile control plane is necessary to share network resources efficiently. The speed of the control plane will increase by four to five orders of magnitude, driven by per-session scheduling of big flows of data on demand. Cognitive networking is a new paradigm of network management and control; it is designed to sense network states and traffic demand automatically and to make decisions on network reconfiguration on the fly, in time scales of seconds, as opposed to tens of minutes today. Professor Chan started the *IEEE Transactions on Cognitive Communications and Networking* three years ago; judging from the submissions, he has found that the communication aspect is rather mature, but the network aspect has a long way to go to establish a good core of results for applications. The RLE program aims to address the toughest issues within this subject:

1. Given that the magnitude of the information states of the network will be large and impossible to capture entirely before network reconfiguration decisions are made, what are the most important network states to gather and use for network decisions?
2. Based on these information states, what are the best (as in fastest and most accurate) algorithms that can perform network reconfiguration quickly to prevent congestion from building up and to provide resilient restorations on network elements failures?

The Chan group's new research paradigm goes beyond current software-defined network development and recent extensions to orchestration, the effort to involve all layers, particularly the optical physical and control layers beyond software-defined networking. The goal is to use algorithms the performance of which can be quantified and in most cases proven to be optimal in metrics relevant to networks in practice (such as delay to end users).

Over the past year, researchers considered a wide-area network reconfiguration problem that demonstrated the efficacy of cognitive optical network management and control. Observing traffic arriving at the metropolitan network and wide-area network gateway nodes, the Chan group will use the algorithm to apply a form of a sequential Bayesian test to decide when to reconfigure. It is the optimal sequential test and its complexity is implementable in practice. The response time is fast enough to prevent delays from occurring when there is a sudden traffic increase. This algorithm works in conjunction with the group's patent on a fast light path setup that changes the setup time from 17 minutes to 50 mS. The result was first announced in July 2017 in an invited paper in

Spain, with a more comprehensive paper published at the IEEE International Conference on Communications at Kansas City, MO, in May 2018. The work has attracted attention from equipment and service providers, who have offered to collaborate, provide funding, and purchase intellectual property. The Chan group has the support of, and collaborates with, four companies—CISCO Systems, Acacia Communications, Plexxi (now part of Hewlett Packard), and Ciena.

The Internet of Things and the Smart City

The IoT, broadly defined, encompasses current sensors, networking infrastructure, and computing and storage elements as well as future (fifth-generation) cellular and fiber architectures, new cognitive networking paradigms for heterogeneous networks, and data analytics. The vast amount of data from sensors and mobile devices, the increased traffic demand from end users, and the ever-increasing number of end users (up to 50 billion worldwide) will require smarter approaches to sensor, network, and computing resources deployment, interconnection, use, and management.

In academic year 2018, Professor Chan's group started a new program jointly with three universities in Hong Kong (Hong Kong University, the Chinese University of Hong Kong, and the Hong Kong University of Science and Technology), in IoT and "smart city" work, with a specific focus on intelligent transportation system problems, such as autonomous vehicle safety. The program is co-funded by the Hong Kong government's Innovation and Technology Commission and several IoT companies.

Urban planners working with IoT can synthesize data from multiple sensors, relay critical information to emergency responders and operational partners, and, potentially, avert crises in applications such as autonomous vehicles. As the number of connected devices grows, computational networking tasks have to be conducted closer to edge devices; low latency and cross-layer protocols that optimize network resource allocation will be needed. In a resource-constrained environment, a concentrated surge in arriving data from a particular region would put significant stress on the network infrastructure. The network's response may include:

- Classifying and prioritizing data from vast IoT sensor networks
- Satisfying appropriate latency requirements by providing priority-based networking and decisions on demand

Professor Chan's group created a new media access control protocol through which priority data would be serviced within a specified delay, while other data would be serviced fairly, not excessively blocked. This medium access control protocol involves other layers (e.g., layer three, the routing layer) to provide end-to-end delay requirements. This protocol represents a major departure from current IoT architectures. The Chan group believes the old architecture cannot provide deadline guarantees unless it uses an unaffordable amount of over-provisioning. The new algorithm adapts dynamically to critical traffic demand and focuses resources to satisfy delay requirements without over-provisioning. This class of delay-guaranteed protocols will likely be central to the new class of networking called ultra-reliable low latency communication, supporting autonomous vehicles, haptic networking, telesurgery, and public safety applications.

The Energy-Efficient Circuits and Systems Group, led by Professor Anantha P. Chandrakasan, investigates new circuit-level and architectural techniques to enable improvements in energy efficiency and security for a wide range of integrated electronic systems. Examples of application domains include security, energy harvesting, and wireless charging for IoT devices, multimedia processing, and biomedical electronics. One research highlight from the group this year was a collaborative project on a gastrointestinal sensing platform with Professor Timothy K. Lu in RLE, who co-led the project, and his student Mark Kyle Mimee, who was co–first author. Visiting Scientist Giovanni Traverso, Professor Robert Langer's group in the Koch Institute for Integrative Cancer Research, and Professor Vladimir Bulović's group in RLE and the Microsystems Technology Laboratories, were also key collaborators.

Many diseases afflicting the human gastrointestinal tract are associated with biochemical signatures that could reveal clues about the current status and likely progression of the disease. Sensing these biochemicals in situ via an ingestible capsule could provide convenient and accurate diagnostic information to help manage the disease. Unfortunately, sensing molecules in the gastrointestinal tract is challenging because of the caustic environment and relative inaccessibility.

In recent work, Professor Chandrakasan's team (Professor Chandrakasan and Professor Timothy Lu, Mark Mimee, and Phillip Nadeau) succeeded in demonstrating an ingestible biosensor based on engineered bacterial cells. The group believes it is the first time that living cells have been used for real-time chemical sensing in the gut. Cells are both naturally adept at sensing molecules present in their surroundings and naturally resilient to many challenging environments, including the gastrointestinal tract. In the group's proof-of-concept demonstration, the cells were engineered to sense heme molecules, which are a major constituent of blood and whose presence would be expected in gastrointestinal bleeding. The cells were packaged inside an electronic capsule with readout circuitry and a wireless transmitter and were exposed to the surroundings via a semipermeable membrane. On exposure, the cells signaled the in-capsule circuitry by luminescence, and the capsule transmitted the measured luminescence levels wirelessly to a nearby laptop or smartphone.

Although the immediate potential application for this work is as a monitor for upper gastrointestinal bleeding in patients at high risk for variceal bleeding, the platform is modular and can be made to sense other molecules by engineering new cellular sensors. Future work is planned to develop new sensors and prove these in animal models, as well to reduce the size of the ingestible capsule to lower the probability of complications.

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 of the past year involved solid-air porous phononic crystal slabs and volumetric reconstruction of tissue electrical properties. Descriptions of these efforts follow.

Shape optimization of solid-air porous phononic crystal slabs with wide, full three-dimensional bandgap for in-plane acoustic waves: The use of phononic crystals as smart materials is growing because of their tunable dynamical properties and the wide range of possible applications of such crystals in structural civil engineering (e.g., acoustic isolation, noise suppression, and vibration attenuation) as well as in MEMS microstructures (e.g., acoustic waveguides, acoustic super-lenses, negative refraction, acoustic cloaking, and energy harvesting). Phononic crystals are periodic structures that exhibit elastic wave scattering for a certain band of frequencies (bandgap), depending on the geometric and material properties of the fundamental unit cell of the crystal. Phononic crystal slabs can be realized by plane-extruded structures composed of a single material with periodic perforations. Several topologies can be found in the literature for phononic crystals with square-symmetric unit cells that exhibit complete two-dimensional bandgaps; however, because of the application demand, it is desirable to find the best topologies to guarantee full bandgaps referred to in-plane wave propagation in the complete three-dimensional structure. Professor Daniel's group developed a shape optimization procedure on the shape of the cell hole, obtaining several topologies with non-square-symmetric unit cells, endowed with complete three-dimensional full bandgaps for in-plane waves. They also adopted model order reduction techniques to reduce substantially the computational time in the wave dispersion analysis. This approach has demonstrated in many cases a doubling of the relative bandgap compared with available state-of-the-art designs. The work was published at MEMS and structural engineering conferences as well as in the Journal in Computational Physics. Further, thanks to a collaboration with Politecnico di Milano, the project has now raised €30,000 for exploring a possible material and structural engineering start-up. There has been demonstrated interest from the tram and the train transportation companies in Milan, Italy.

Volumetric reconstruction of tissue electrical properties from B1+ and MR signals using global Maxwell tomography: theory and simulation results: Classical magnetic resonance reconstructs images on the basis of the water content of different tissues. In the Daniel group's global Maxwell tomography approach, the scattered electromagnetic fields employed by classical magnetic resonance were used to reconstruct electrical properties of tissues—permittivity and electrical conductivity. In particular, the group has developed a global tomography mapping technique with two new cost functions and an extension that uses piecewise linear basis functions to represent fields for higher accuracy. The technique is fully three-dimensional. The team validated its approach with various numerical experiments, using a heterogeneous head model with realistic electrical properties and a physical phantom constructed with tissue-mimicking electrical properties. The work showed, for the first time, that artifact-free, accurate, and robust-to-noise reconstruction of electrical properties is possible. Changes in electrical conductivity have been shown to be related to cancer cells. In the immediate future, the Daniel group will move on to in vivo validation in collaboration with the New York University Radiology Department.

Professor Jacob K. White leads the Computational Prototyping Group with Professor Luca Daniel. There have been significant accomplishments over the past year in three areas: the successful introduction, in spring 2018, of five design experiences into the technology enabled active learning (TEAL)–based 8.02 Physics II; the extension of the Computational Prototyping Group's fast voxel-based methods (originally developed for magnetic resonance imaging [MRI] field analysis) to nano-photonic and on-chip inductance analyses; and hardware and software for magnetic resonance imager static field manipulation for standard, spectroscopic, and zoomed-region imaging.

Design Experiences in TEAL-based Freshman Electromagnetics: Five design-oriented laboratory assignments (developed with Suzannah A.Fraker, M. Al Ai Baky, Edward Z. Fan, and Peter Dourmashkin, with support from EECS, the Department of Physics, and the Alumni Fund) were introduced to five TEAL sessions for one section of the spring 2018 term of 8.02 Electricity and Magnetism 1. The laboratory exercises were the optimization of the geometry of a capacitance-based accelerometer, conductor shape optimization for a resistor piano, magnet and coil placement optimization for both a brushless motor and a generator, and coil design for resonance-based wireless power transfer. Current plans are to use the laboratory assignments in 8.021 in the fall of 2018, and for all sections of 8.02 in spring of 2019.

Fast simulation for magnetic resonance imager fields, nano-photonics, and on-chip inductance (MARIE, VoxHenry, and VoxPhoton): The Computational Prototyping Group continues to collaborate with colleagues at the MIT–Skolkovo Institute of Science and Technology (Skoltech) on MARIE, the fast voxel-based fields-in-tissue simulator for magnetic resonance imager applications, but have been more focused on new applications. Recent developments in effective absorbers, partitioned-circulant preconditioning, and fast frequency sweeping are making VoxPhoton a compelling tool for analyzing complicated nanophotonic structures. It is already being used for performance and manufacturing variability analysis for nanophotonic ring resonators, Bragg grating, couplers, and splitters (work done with Scott Groth and Athanasios Polimeridis and Alexandra Tambova from Skoltech). VoxHenry, the new on-chip inductance extractor that can analyze billion-voxel structures on a laptop, uses the group's recently developed translation-invariance-preserving plus current-conserving-around-corners basis functions. VoxHenry has been demonstrated on a variety of benchmark structures, including square and circular coils (with and without substrate ground planes) and arrays of radio frequency inductors (collaborative work with Abdulkadir Yucel of Nanyang Technological University, Singapore).

Quasistatic (B0) field manipulation in MRI: The group's fast-updating coil-current drivers, paired with efficient convex-optimization-based coil-current selection algorithms, is expanding the role of B0 field manipulation in MRI sequences. B0 manipulation has been demonstrated for homogenization in standard imaging, selective excitation in spectroscopy applications, and zooming for single-structure brain imaging (with Nicolas S. Arango, Irene A. Kuang, Elfar Adalsteinsson from EECS, and Jason Stockmann, Lawrence Wald, and John Pauly from Massachusetts General Hospital).

Professor Jeffrey C. Grossman, Goulder Professor of Materials Science and Engineering, and his team focus their efforts on the computational and experimental design of novel materials for applications in energy conversion, energy storage, and separations. Significant results in AY2018 included the fabrication of a new nanoporous silicon membrane that can filter 2-nanometer (nm) particles while exhibiting extreme resilience (negative pH and temperature higher than 300° Celsius), a first of its kind. The group has also developed new machine learning algorithms capable of rapidly screening solids, and applied this method to design polymers with higher ion conduction for battery applications. The Grossman group has also developed a new transparent heater made from tar, which is a negative-cost material, that, compared with the best alternatives made from nanowires, can reach much higher temperatures without degrading.

Professor Jae S. Lim's group is involved in the development of image and video processing methods. During this past year, they published the results of their work on the experimental verification of a prediction from a simple model developed for color images, in the *Journal of Imaging Science and Technology*. 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 and the Laboratory for Information and Decision Systems within MIT. Outside MIT, collaborators include Ben Gurion University, Battelle Memorial Institute, BBN Technologies, Brown University, the Budapest University of Technology and Economics, CodeOn Technologies, Duke University, École Polytechnique Fédérale de Lausanne, ETH Zurich, Maynooth University, National Jiaotong University, Nokia, Northeastern University, Pennsylvania State University, Stanford University, Technische Universität Braunschweig, Technische Universität Dresden, Technion (Israel Institue of Technology), the University of California, Davis, the University of California, Los Angeles, Universidad Carlos III de Madrid, University College Cork, University of Cyprus, the University of Delaware, and Trinity College Dublin. The group's focus is networking, with a special emphasis on new practical and theoretical developments in the area of network coding. Some specific achievements during the past year included a noise-based decoding algorithm that is capacity achieving and promises to speed up communications circuits considerably; the use of network coding in fifth-generation wireless systems requiring very low delays; the design of waveforms for wireless communications, and the use of coding in distributed storage with hardware placement constraints. Professor Médard received the IEEE Edwin Armstrong Award and the Test of Time Award from the Association for Computing Machinery Special Interest Group on Data Communication.

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 multimedia applications such as computer vision, machine learning, and video compression. Their work traverses various levels of abstraction, from energy-aware algorithm development for signal processing to efficient architecture design and low-power, very large-scale integration circuit implementation. The group's work this year has been concentrated on three areas: joint architecture and algorithm design for energy-efficient real-time visual inertial odometry for drone navigation; energy-efficient algorithms for deep neural networks, which give state-of-the-art accuracy on a wide range of machine learning tasks (e.g., object classification, speech recognition); and energy-efficient depth estimation to reduce the on-time of time-of-flight sensors. Their work in co-designing algorithms and hardware for energy-efficient visual inertial odometry (in collaboration with Sertac Karaman of the Department of Aeronautics and Astronautics) makes achieving real-time perception on a drone with less than 24 mW feasible; this is three orders of magnitude below existing off-the-shelf solutions. This is an important step toward enabling autonomous navigation for small (bottle-cap-size) drones. The Sze group's work on algorithms that automatically tailor deep neural networks for a given embedded platform using direct empirical measurements enabled a 1.7-times reduction in latency while maintaining or improving accuracy. The group also showed that with lightweight algorithms they could reduce the on-time of time-of-flight sensors by five times, with less than a 1% reduction in mean relative error. Reducing the sensor on-time of time-of-flight sensors reduces the overall system power use as well as interference in applications with multiple time-of-flight sensors (e.g., when multiple users use augmented reality).

During academic year 2018, Professor Gregory W. Wornell's research focused on three areas. One was new technology and algorithms for advanced sensing, data acquisition, and information security; the second was new techniques for computational imaging and vision in complex environments; and the third was principles of learning in physical systems and embedded applications.

In data acquisition, Professor Wornell's group developed and analyzed a new analog-to-digital converter architecture that promises significant improvements in performance over traditional designs. In existing systems, if the analog input has structure, it can generally be efficiently exploited only after data conversion, which necessitates high (intermediate) conversion rates. This research showed how to avoid this problem. Key to the new converter is applying a modulo operation to the input before quantization, combined with appropriately designed digital signal post-processing. As one application of the methodology, researchers developed an oversampled modulo analog-to-digital converter, for which they described a phase-domain implementation based on ring oscillators. Analysis suggested that the resulting design is a compelling alternative to sigma-delta conversion, to which it is naturally compared. Extensions to multichannel converters were also developed. These have a variety of potentially important applications, including massive multiple input–multiple output technologies for fifth-generation and other future wireless networks.

In the Wornell group's work on information security, they developed new results on the problem of covert communication. Earlier analysis had shown that, when subject to the constraint that transmission is not detectable, reliable communication is generally not possible at positive rates. The number of bits per second that can be communicated is proportional to the square root of the bandwidth, compared with being proportional to the bandwidth without the constraint. The Wornell group's recent analysis showed that, surprisingly, the introduction of channel state information (e.g., a jamming pattern) that is known to the transmitter, but to neither the intended receiver nor an eavesdropper, overcomes this square-root limitation. In particular, strictly positive rates for covert communication are possible. This result has implications for the design of systems for a variety of defense and related applications.

Members of the Wornell laboratory also developed new lensless camera architectures that replace the traditional camera lens with a physical mask that controls which parts of the light from the image of interest reach different pixels on the sensor. Although the intensities recorded on the sensor are not directly interpretable as an image, the desired image can be recovered by suitable digital post-processing of the sensor data. Analysis of the results revealed the relationship between the quality of image reconstruction and the choice of mask, as a function of the sensor noise characteristics, including both thermal and shot noise. Researchers developed an information-theoretic framework for mask optimization and showed that suitably designed pseudo-random masks can be near optimal and offer high-quality reconstructions. These results have the potential to affect future designs of cameras and imagers for diverse applications. The methodology also allows comparison of the relative value of different accidental occluding structures in a natural environment with respect to their ability to allow us to see around corners, that is, enable non-line-of-sight optical imaging.

Professor Lizhong Zheng took sabbatical leave in academic year 2018. During this time, he visited Shenzhen, China, where he was a visiting professor at the Tsinghua-Berkeley Shenzhen Institute. He also worked with local companies, including the artificial intelligence laboratories of Tencent, Huawei, and Foxconn, on a number of research projects covering natural language processing, recommendation systems, physical layer communication channels, and smart manufacturing. His work on universal feature selection, which gives an information-theory interpretation to deep neural networks, received both academic and industrial interest.

Biomedical Science and Engineering

This research theme encompassed work in bioinspired electronics and neural prostheses for hearing and sight; nanotechnologies and microtechnologies for understanding and manipulating biological processes at the cellular and molecular level; imaging and computational modeling of disease and neuroanatomical processes; and communication biophysics (language, speech, hearing, and haptics), including speech synthesis and recognition, sensory communication in all modalities, and the physiology of auditory perception and speech production.

MRI has been a transformative medical imaging modality for diagnostic and scientific applications in adults, but its applications in pregnancy remain limited and progress is hindered by the unpredictable motion of the fetus. Further compounding the problem is MRI equipment that fits pregnant women poorly. Current fetal MRI relies on a severely compromised image acquisition stage to mitigate the degradations in diagnostic quality caused by the subject's motion. Professor Elfar Adalsteinsson's research group has increasingly focused its attention on these motion-caused problems for fetal imaging with MRI. This work on obtaining good images of the fetus and placenta is supported by the National Institutes of Health, with teams of colleagues at MIT, the Martinos Center at Massachusetts General Hospital, and Boston Children's Hospital.

Another active research area for the group is magnetic resonance spectroscopy. In particular, the group is interested in the design of algorithms for optimization of main magnetic field inhomogeneity for a novel kind of hardware called a shim array. The shim array was developed by colleagues at the Martinos Center. Graduate student Nick Arango, in collaboration with his advisor, Professor Jacob White, developed new algorithms and optimization for the spectroscopic imaging application.

The Bioelectronics Group, led by Professor Polina Anikeeva, develops optoelectronic and magnetic interfaces to the nervous system. Over the past year, this team developed magnetic nanomaterials and power electronics to drive neurons wirelessly via magnetically triggered local heating in behaving rodents. For example, by packaging pharmacological compounds into heat-sensitive liposomal carriers, the Anikeeva group achieved repeatable and reversible activation of drug-receptor pairs, which permitted control of motivated and social behavior in mice. The magnetothermal effect was expanded to multiple particle chemistries and magnetic field conditions, allowing multiplexed control of several independent cellular processes or neural circuits.
In addition to magnetothermal actuation, the Anikeeva team explored anisotropic nanomaterials as transducers of mechanical torques in slowly varying weak magnetic fields. The team has also collaborated with Xuanhe Zhao's group in the Department of Mechanical Engineering to create adaptive and stealthy multifunctional probes based on microscale polymer-based multimaterial fibers and tough hydrogels. By direct polymerization of hydrogels onto fiber surfaces, the groups have integrated multiple functional elements (electrodes, optical waveguides, and microfluidic channels) into mechanically adaptive structures that exhibited gigapascal modulus in the dried state and kilopascal modulus when fully hydrated. This property facilitated the implantation of the probes into deep brain regions and simultaneously minimized the foreign body response, enabling tracking of isolated action potentials in the brains of freely moving mice for more than six months. The team expects that this technology will enable fundamental studies of the electrophysiological underpinnings of progressive disorders, such as Parkinson's disease and Alzheimer's disease.

Professor Louis D. Braida and the Sensory Communication Group investigated topics in three broad areas: hearing aids, the tactile communication of speech, and auditory-tactile interaction.

The major focus of the group's research during the past year has been on the development of tactile aids to speech communication. The long-term goal of the tactile-aid research is to develop improved aids for persons with profound sensorineural hearing or visual impairments, or both. Tactile communication systems can serve as sensory substitution aids to provide information about acoustic stimuli in the environment, including speech and other types of environmental sounds. In light of technical advancements in several areas (including signal processing, automatic speech recognition, and new approaches to training and learning with novel displays), an opportunity now exists to develop and evaluate a new generation of tactile aids with the capacity for achieving speech communication through the sense of touch alone.

Over the course of the past year, the Braida group conducted a series of experiments with a tactile device consisting of a four-by-six array of vibrators that are fitted around the user's forearm between the elbow and the wrist. The approach has been to develop a unique haptic code for each of the 39 phonemes of the English language, which can then be concatenated to form words and sentences. The codes for consonants are static vibratory patterns on the array that encode some of the features of speech production, such as place of production and duration. The codes for vowels consist primarily of moving patterns of vibrations at different locations and directions on the tactile array. Experiments were conducted in which participants were trained to identify the 39 haptic phonemes individually, followed by training and testing in the identification of words and pairs of words composed of the haptic symbols.

Because training is crucial in the use of a novel display of speech codes, a number of steps were taken to facilitate learning how to use the tactile device to understand phonemes and words. Phonemes were introduced in small groups and were combined to form words until the full set of phonemes had been introduced. Training was also provided through the use of an identification paradigm with correct-answer feedback. In tests conducted without feedback, the majority of participants achieved a rate of phoneme recognition that was more than or equal to 90% correct within several hours of training and were able to identify closed sets of 100 words with a similar degree of accuracy. Trained participants were able to identify a set of 500 words with an accuracy of 85% correct and were also able to interpret two-word phrases at a communication rate of roughly 30 to 40 words per minute. Studies have demonstrated continued improvements in vocabulary size and communication rates as users become more proficient in the use of the tactile display.

Persons who are both deaf and blind and are experienced in the use of natural methods of tactual communication have made it clear that communication through the skin is possible. Current research has expanded the horizons of tactual communication through the development of an artificial display in which speech stimuli can be learned and perceived through the tactile sense alone. This research provides benefits not only to persons with profound sensory deficits, in terms of giving them greater access to the word around them, but also has broader applications for persons with normal sensory abilities in situations where hearing and sight may be diminished or busy with other tasks.

The research in Professor Dennis M. Freeman's group focused on the cochlear mechanisms that underlie the extraordinary properties of our sense of hearing, especially on the sensitivity to low-amplitude sounds and acute frequency selectivity that are hallmarks of mammalian hearing. The group had shown that the tectorial membrane, which is a gelatinous structure that stimulates the sensory receptor (hair) cells in the inner ear, supports traveling waves of motion; these traveling waves play a key role in shaping the frequency selectivity of hearing. Work during the past year focused on understanding interactions between the tectorial membrane and the sensory receptor cells. The sensory receptor cells are stimulated via a microscopic bundle of sensory hairlike projections called stereocilia. The stereocilia of outer hair cells are thought to be mechanically anchored to the tectorial membrane, and thereby stimulated to move in phase with it. However, the tectorial membrane is highly hydrated (96% water by weight), and the molecular mechanisms underlying the mechanical properties of the tectorial membrane depend on both the elastic properties of the matrix and the viscous properties of the interstitial fluid. Fluid flow through the nanoporous structure of the tectorial membrane can directly affect the nanometer-scale motions of the hair bundles. To investigate the nanoscale interactions of the tectorial membrane with hair bundles, researchers stimulated the tectorial membrane dynamically at audio frequencies, using atomic force microscopy probes with dimensions comparable to the diameter of the hair bundles. They observed elastic forces at both low and high frequencies, and a surprising presence of viscous forces near transition frequencies. This hybrid viscoelastic behavior produces a frequency-dependent phase lead of up to 90 degrees that had not been previously reported. Such a phase lead would tend to compensate for electrical, mechanical, and hydrodynamic phase delays that must be overcome for cochlear amplification. These results have significant consequences for understanding the mechanisms that underlie the sensitivity and frequency selectivity of hearing, and could have application to the clinical diagnosis and treatment of hearing disorders.

Professor James G. Fujimoto leads the Biomedical Optical Imaging and Biophotonics Group in RLE, 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, the Tuft University School of Medicine, New York University, and Oregon Health and Sciences University. They conduct gastroenterology and endoscopic studies at the Harvard Medical School and Boston Veterans Administration 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 in the early 1900s for the invention of OCT, for its commercialization by Carl Zeiss AG for applications in ophthalmology and for the commercialization by LightLab Imaging of OCT in interventional cardiology. OCT has become a standard diagnostic procedure in ophthalmology, with an estimated 20 million to 30 million ophthalmic OCT imaging procedures worldwide every year. OCT is also an emerging imaging modality for intravascular applications and is being developed in many other clinical and fundamental research applications.

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. Researchers recently completed the design and development of two new high-performance OCT instruments, a swept-source OCT instrument that doubles imaging speeds and a spectral-domain OCT instrument that achieves ultrahigh resolution and high speed. Imaging studies with patients at the New England Eye Center began in summer 2018.

Working in collaboration with the Boston VA Healthcare System, the Fujimoto group is investigating endoscopic three-dimensional OCT for detecting dysplasia in the upper gastrointestinal tract, to guide biopsy instruments, 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. This research is highly challenging because of the demanding clinical workflow and performance required for intraoperative cancer assessment.

Professor Fujimoto received an honorary doctorate from the Faculty of Engineering at the Fredrich Alexander University of Erlangen–Nürnberg; the degree was awarded in a ceremony in Erlangen, Germany, in January 2018. The Fujimoto group has maintained an ongoing collaboration with researchers at the Fredrich Alexander University for more than 10 years.

Increasing costs and decreasing opportunities: Research assistant costs in EECS increased by approximately 13% in one year, making the contract cost of graduate students about $95,000 per year. The amounts of research contracts have not increased; fewer people can be supported and those who remain must produce more research results. Most graduate students can no longer produce the research and engineering results that sponsors require, which forced a restructuring of the research group. Research assistants have been cut to the lowest number in the past 20 years, but the number of postdoctoral associates has increased. The recent cost increases are especially damaging for benchtop and hardware groups because these fields have high M&S costs.

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

Science: The group's work demonstrated a noninvasive technique to identify people who have dangerously low neutrophil (white blood cell) levels. One intended use for this technology is in the context of chemotherapy. Chemotherapy reduces white blood cell levels; when these levels are very low, patients are at heightened risk of acquiring an infection. Currently, a blood test is required to identify dangerously low levels. This technology offers the potential for regular monitoring at home. Results from the first clinical test were encouraging. The work has garnered many awards in business competitions and, thanks to new funding from the Small Business Innovation Research program, will form the basis for a new start-up, Leuko Labs. Carlos Castro, the team lead, was a graduate of both MIT's Catalyst Program and the Translational Fellows Program.

Fostering Innovation: The MIT Catalyst Program (born in RLE through the Madrid-MIT M+Visión Consortium, now MIT linQ) continues to demonstrate an accelerated pace and volume of innovation. As of June 30, 2018, seven of the 16 MIT Catalyst projects had gone through a transition to commercial development, either through licensing to start-ups (five projects) or to existing ventures (two projects). During FY2018, technology from two of the group's projects was licensed to start-ups. Professor Gray's group hopes to extend this successful track record with the Catalyst cohort that will arrive in fall 2018. In recognition of Professor Gray's leadership in biomedical innovation (through her work as director of the Harvard-MIT Division of Health Sciences and Technology, the Madrid-MIT M+Vision Consortium, and MIT linQ), she received the Memorial Award from the Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado (Civil Servants Social Security and Services Institute, a Mexican government institution that provides social and healthcare services for civil servants) in March 2018.

Career development: The MIT IMPACT Program provides a semester-long experience for Boston-area trainees (postdoctoral associates and advanced predoctoral associates) to help them become more strategic in their research and career plans; the aim is to increase the chance of making a real-world impact. Independent program evaluations revealed that 94% (of approximately 100 participants) would recommend the program to others, and many participants commented on the experience with adjectives such as "transformative" and "enlightening." This program received the 2018 Program Award for a Culture of Excellence in Mentoring at Harvard Medical School.

Cultivating diversity for research careers: The Gray group launched its second Rising Stars workshop in biomedical technology. This edition of the workshop focused on high-potential members of underrepresented minority groups who are nearing their entry to independent careers in academia or industry. They came to MIT in November for a two-day workshop specifically designed for those seeking research-oriented careers.

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

During academic year 2018, Professor Han's Singapore-MIT Alliance for Research and Technology center research team, led by Yin Lu, published two seminal papers on using high-throughput microfluidic cell sorting to improve various cell therapy applications. Cell therapy is considered to be the future of human medicine. It has been drawing considerable attention because of the recent approval by the US Food and Drug Administration of chimeric antigen receptor T-cell therapy, but it is currently limited by the challenges of producing enough therapeutic cells reliably and of ensuring the efficacy and safety of the produced cells by purifying often heterogeneous cell populations. Researchers in the Han group, in collaboration with the National University of Singapore's Tissue Engineering Program, applied high-throughput cell sorting for isolating and purifying heterogeneous mesenchymal stromal cells or chondrocytes (for cartilage repair), resulting in better growth of cells as well as better functional outcomes. Just as in conventional drug therapies (small molecules and biologics), purification and separation of any therapeutic cells to be injected or implanted in the human body will be crucial to clinical translation of many cell therapy modalities. The Han group's work on chondrocyte sorting led to a $1.5 million (Singapore dollars) grant, enabling studies in a larger-animal (pig) model for the next-level validation.

Professor Thomas Heldt directs the Integrative Neuromonitoring and Critical Care Informatics Group at RLE and MIT's Institute for Medical Engineering and Science. Using physiologically based dynamic models, Professor Heldt's group leverages multivariate bedside monitoring data—on timescales of a second to an hour—to understand the physiology of the injured brain, to improve diagnoses, and to accelerate treatment decisions in the critically ill. Professor Heldt's group continues very strong and active collaborations with clinicians at Boston Children's Hospital, Boston Medical Center, Massachusetts General Hospital, and Beth Israel Deaconess Medical Center in the areas of neurocritical and neonatal critical care, as well as other areas of patient monitoring.

Over the past year, the collaboration between Professor Heldt's group, Dr. Andrew Reisner, and Dr. Michael Filbin analyzed patterns of care for patients with sepsis at the Massachusetts General Hospital's Department of Emergency Medicine. The group discovered that septic patients who come to the Emergency Department with vague symptoms that may not immediately point to an infectious etiology are at much greater risk of death than those patients in whom infection is leading the differential diagnosis. This work has been corroborated in an independent multicenter cohort study and will be published in the journal *Critical Care Medicine*. Additionally, the team's "shock precaution on triage" sepsis risk score has now been rolled out across all hospitals in the Partners Healthcare system.

In neonatal intensive care, Professor Heldt's team continued to collaborate with Dr. Wendy Timpson and Dr. Munish Gupta at the Beth Israel Deaconess Medical Center's Department of Neonatology. Over the past year, the team provided a detailed characterization of the bedside monitoring alarm burden in the medical center's neonatal intensive care unit and executed an interventional study that reduced the incidence of tachycardia alarms by a factor of two without increasing the risk to the infants.

Professor Han's group has now validated its model-based, calibration-free, noninvasive approach to continuous intracranial pressure estimation in a diverse set of patients ranging in age from two years to more than 70 years. The approach allows estimation of pressure in conditions with a diverse set of etiologies, including traumatic brain injury, hydrocephalus, stroke, cerebrovascular malformations, and metabolic disorders. The estimates continue to compare well with the clinical gold standard and to outperform some of the invasive intracranial pressure measurement technologies that are still in occasional use.

Professor Timothy Lu's Synthetic Biology Group made several major advances this year. These included:

Synthetic RNA-based immunomodulatory gene circuits for cancer: Immunotherapy is promising for cancer treatment, but its effectiveness has been limited. Researchers in Professor Lu's group have developed gene circuits that harness the immune system to attack a cancer, overcoming existing limitations in therapeutic approaches. They screened their library of synthetic promoters for those most highly active in specific cancer types. They then constructed genetic circuits that are activated only in a given type of cancer cell (not healthy cells) and that encode immunomodulatory elements—surface T-cell engagers that recruit T cells to the cancer cell and immunogenic proteins that elicit strong anti-tumor responses. The genetic circuits have an RNA-based AND gate that generates combinatorial immunomodulatory outputs only when two promoters are active; thus, the circuits are active only in cancer cells. Members of Dr. Lu's laboratory demonstrated proof of concept with human ovarian cancer cells, both in vitro and in vivo. The circuits triggered selective T cell–mediated killing of cancer cells but not of normal cells in vitro. When the circuits were delivered by a lentiviral vector in a mouse model of ovarian cancer, tumors were significantly reduced and mouse survival was prolonged. Researchers plan to apply this platform to other cancer types.

An ingestible bacterial-electronic system to monitor gastrointestinal health: Available disease-monitoring systems cannot yet examine the gastrointestinal tract directly, in situ. For early and precise diagnosis of inflammatory bowel disease and other gastrointestinal disorders, members of the Lu laboratory built an ingestible micro-bioelectronic device harboring bacteria that emit a luminescent signal when they detect a particular marker or disease state. The signal is detected externally (wirelessly) and recorded as an electronic readout. As proof of concept, gastrointestinal bleeding was detected in swine by positioning a heme-sensitive probiotic within the biosensor. This detection platform is modular and extensible; the design could lead to the discovery of biomarkers for multiple gastrointestinal conditions.

Randomized clustered regularly interspaced short palindromic repeats (CRISPR)–associated 9 (Cas9) screening for alpha-synuclein toxicity: Parkinson's disease is characterized by the accumulation of alpha-synuclein (αSyn) in dopamine-secreting neurons in the substantia nigra and ultimately by the death of these cells. Researchers used CRISPR-Cas transcription factors (crisprTFs) to identify combinatorial transcriptional changes that protect against αSyn toxicity. The perturbation of transcriptional networks with CRISPR-Cas9 technology has primarily involved systematic, targeted gene modulation. In this case, however, members of Dr. Lu's laboratory developed a screening platform that uses randomized crisprTFs to globally perturb transcriptional networks. By applying a platform called perturbing regulatory interactions by synthetic modulators to a yeast model of Parkinson's disease, they identified guide RNAs that modulate transcriptional networks and protect cells from αSyn toxicity. Genes differentially modulated by the most protective guide RNA rescued yeast from αSyn toxicity when overexpressed, and human homologs of some of the identified genes were protective against αSyn-induced cell death in a model of human Parkinson's disease. Transcriptional networks identified by randomized crisprTFs may be able to modulate disease.

Other work in the Lu laboratory this year involved scaling computation and memory in living cells, advancing the discovery of antimicrobial peptides, building yeast production platforms for antimicrobial peptides and other biologics, and three-dimensional printing of living responsive materials.

Principal Research Scientist Stefanie Shattuck-Hufnagel's research group had three major themes this year. They appeared within the group's work 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;
- Tests of 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. It may also make it possible to teach second languages in a way that reduces or eliminates a foreign accent.

Members of Shattuck-Hufnagel's group expanded their investigations of the cognitive process of speech production planning and speech perception. They include a focus on individual acoustic cues to the distinctive features that define and contrast the phonemic categories of a language. In this way, their work has supplemented continuing investigations of speech prosody, co-speech manual gesturing, and speech development in children.

- With regard to prosody, they have found that the number of individual acoustic cues present at a prosodic phrase boundary predicts the likelihood that a listener will perceive a boundary at that location. This finding suggests that both speakers and listeners represent and manipulate individual acoustic cues to contrastive categories. If this view is confirmed by further research, it has the potential to inspire a very different view of human speech processing from the current mainstream, with substantial implications both for modeling human processing and for developing automatic speech recognition algorithms that fail in a more natural and user-friendly manner.
- With regard to co-speech manual gesturing, they have reported preliminary evidence that higher-level prosodic constituents (such as groupings of intonational phrases) are signaled by the duration of silence between words, and that this higher-level constituent structure is reflected in the grouping of hand gestures by cues such as trajectory shape. Such findings again suggest that speakers and listeners manipulate individual cues to linguistic structure, and also that speech production planning models must include the process of planning co-speech gestures of the hands and other body parts that speakers often use to gesture.
- With respect to speech development, they have found that toddlers aged 2 to 3 years produce a complex intonational prominence marker for phrase-level prominence (i.e., the complex bitonal pitch accent High+Downstepped High), suggesting that, even at this young age, children are in control of much of the adult inventory of pitch accent types. Such findings cast doubt on the currently dominant view that small children cannot accurately control the fundamental frequency of their utterances.

In collaborative work on speech disorders, with Dr. Juan Godino of the University of Madrid, researchers in Shattuck-Hufnagel's group have shown that an individual-feature-cue–based approach to the analysis of the speech produced by patients diagnosed with Parkinson's disease shows considerable promise for early diagnosis of this disorder, during the period of time when treatment can still be effective. These results suggest that Parkinsonian speech is distinct from that of typical speakers, not only for the traditional diagnostic stop consonants /ptk/, but for almost all of the vowels and consonants. If confirmed by additional analyses, this approach would provide substantially more detailed information about the course of the disease in each patient, potentially also shedding light on the effects of Parkinson's disease on each of the various neurological systems used to control the activity of different parts of the vocal tract during speaking. Taken together, these results highlight the value of a multidisciplinary approach to investigating the cognitive process of human speech processing.

Professor Collin M. Stultz and the Computational Biophysics Group focus on the development of computational tools that improves the understanding of fundamental biochemical processes that play a role in human disease. They are also using machine learning to improve the care of patients with cardiovascular disease.

Professor George C. Verghese directs the Computational Physiology and Clinical Inference Group, which 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 Thomas Heldt's research group on integrative neuromonitoring and critical care informatics. Several clinical collaborators also participate in the research.

The main direction of research in the group is aimed at more extensive and refined use of time-based capnography, which records the partial pressure of carbon dioxide as a function of time in exhaled breath. Capnographs are ubiquitous in hospital settings and ambulance systems, and provide a noninvasive and effort-independent monitoring modality, 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 Dr. Baruch Krauss at Boston Children's Hospital and of his clinical collaborators in various hospitals, who have collected valuable original data.

After initial explorations using methods inspired by machine learning, the group has now turned to developing simple mechanistic models for the capnogram, with clinically meaningful parameters that can be identified in real time during patient monitoring and then used to assess patient status. 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, was published in *IEEE Transactions on Biomedical Engineering* in December 2017. The algorithms described in the paper were very effective in distinguishing patients with chronic obstructive pulmonary disease from normal subjects on the basis of two to three minutes of natural respiration. The methods also showed promise in tracking the respiratory state of asthma patients as their breathing worsened with controlled administration of a bronchoconstrictor and then recovered on administration of a bronchodilator.

Subsequent work by the group has enhanced the model to allow mechanistic representation of lung inertance associated with the pulmonary edema that occurs in congestive heart failure. In a paper titled "An Enhanced Mechanistic Model for Capnography," written with former student Ekin Karasan and accepted for oral presentation at the July 2018 IEEE Engineering in Medicine and Biology Conference, accuracy of greater than 85% was obtained in distinguishing between capnograms from patients with congestive heart failure and patients with chronic obstructive pulmonary disease in a test set, through a classifier designed on a training set and acting on breath-by-breath estimated model parameters. A two-year project that has just begun under industrial sponsorship will develop and test these algorithms further on capnographic data recorded alongside other standard monitoring data in two collaborating hospitals. Data will come from children with asthma as well as adults with congestive heart failure or chronic obstructive pulmonary disease.

Professor Joel Voldman's research interests focus on BioMEMS, applying microfluidics to illuminate biological systems and solve medical challenges, ranging from point-of-care diagnostics to fundamental cell biology. Professor Voldman and the Biological Microtechnology and BioMEMS groups worked on several areas this past year. One was in the area of sensing of biomolecules. Sensing biomolecules (proteins, metabolites, and so on) in biological fluids (blood, urine, and so on) is an integral part of medical practice. Many groups are developing methods to make accurate measurements at the point of care. Professor Voldman's group developed an approach to making those measurements using inexpensive hardware that is easily scalable to measuring 10s of molecules (reported in *Biosensors and Bioelectronics*). 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 visually tracked as they traverse a playground of different measurement structures, was described in an oral presentation at the 2017 Miniaturized Systems for Chemistry and Life Sciences conference and in a 2018 paper in *Lab on a Chip*. A related paper demonstrated the ability to make multiple measurements of the electrical properties of cells.

Nanoscale Materials, Devices, and Systems

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

Professor Karl Berggren's research group develops nanofabrication methods for applications in quantum technologies and nanotechnologies. The main 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 recently developed a scalable detector array that can resolve multiple photons over a large number of positions. This detector uses a single continuous superconducting nanowire where electrical signals propagate more than 50 times more slowly than in free space. By varying the width at different sections, the nanowire serves as either a photon-sensitive detector segment or a compact delay line. In a 16-element device, the group demonstrated timing-logic-based operation that resolved all 136 possible single-photon and two-photon coincidence events. With a four-element device, they demonstrated photon number resolution by performing pulse shape processing. Regardless of the array size, the device requires only two readout lines, which solves the critical problem of thermal load in operating superconducting devices at cryogenic temperatures. This device is useful for on-chip multiphoton coincidence counting and may provide a practical solution for implementing large-scale photonic quantum information processing systems.

In the past year, Professor Berggren's group also investigated control of electrothermal dynamics in superconducting nanowires for the development of new nonlinear devices. By placing a shunt resistor in parallel with a superconducting nanowire, it was possible to create rapid oscillations between superconducting and non-superconducting states. A study of these oscillations showed that their frequency is tunable and may be calculated through a simple expression, and found that the maximum frequency may be on the order of 1 gigahertz. Furthermore, these relaxation oscillations were capable of mixing with an external microwave drive and eventually locking to the drive frequency. The group found that the locking process creates distinct signatures in the current-voltage characteristics of the device that occur at quantized voltage intervals relating to the flux loaded during a relaxation oscillation cycle. Discovery of this fundamental relationship and control of the relaxation oscillations by an external drive paves the way for new nanowire-based devices that may be used in technologies such as frequency modulation or parametric amplification.

The world of quantum mechanics holds enormous potential for addressing unsolved problems in communications, computation, and precision measurements. Efforts are underway across the globe to develop such technologies in various physical systems, including atoms, superconductors, and topological states of matter. Professor Dirk Englund's research 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 so-called 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, and ultra-precise global positioning systems. Over the past 12 months, the Englund group developed improved interfaces between photons and quantum memories in the form of electron spins in diamond clusters of several individually addressable spin qubits; identified a promising new diamond color center, the lead-vacancy emitter; and demonstrated a backbone to connect such atomic emitters through a photonic integrated circuit based on aluminum nitride that achieves record-quality optical resonators in the ultraviolet spectrum. They also demonstrated an advanced quantum key distribution protocol over the recently established MIT Lincoln Laboratory dark fiber link, using novel photonic integrated circuit transmitters.

- 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. In a collaboration with Professor Frank Koppens of the Institute of Photonic Sciences (Instituto de Ciencias Fotónicas), members of the Englund group pushed plasmon confinement to the ultimate length limits of single atomic layers.

- A major new direction in the Englund group is to develop ways of patterning atomically thin two-dimensional materials with atomic precision, to produce ideal quantum materials with desired properties engineered atom by atom. In that direction, the Englund group recently explored bolometric devices based on single-layer graphene that resulted in a new type of ultrafast bolometric photodetector. A collaboration between Professor Karl Berggren and Professor Englund resulted in an important advance in chip-integrated superconducting single-photon detectors.

Professor Englund is the principal investigator of the Air Force Office of Scientific Research's Multidisciplinary University Initiative program called Optimal Measurements for Scalable Quantum Technologies, and also of a new NSF Emerging Frontiers in Research and Innovation program on quantum repeaters. These programs include principal investigators from MIT and collaborators from Harvard University, Yale University, and the University of Maryland. Englund is also principal investigator on a new US Army Research Office Multidisciplinary University Initiative program on quantum materials.

Fibers are among the earliest forms of human expression, yet have remained surprisingly 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 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. This approach uses two complementary strategies toward realizing sophisticated functions: on the single-fiber level, the integration of a multiplicity of functional components into one fiber, and on the multiple-fiber level, the assembly of large-scale fiber arrays and fabrics. These multimaterial fibers offer unprecedented control over material properties and function on lengths that span the nanometer to kilometer range.

Fink's research continues to provide the basis for the NSF's Materials Research Science and Engineering Centers Interdisciplinary Research Group on fiber fluid instabilities. He is joined by other RLE principal investigators, Polina Anikeeva, John Joannopoulos, Steven Johnson, and Marin Soljacic.

The research of Professor Jing Kong and the Nanomaterials and Electronics Group focuses on the challenge of developing the chemical vapor deposition synthesis routes of various two-dimensional materials, characterizing their structures and properties, and developing their applications. Group members are designing new strategies to make graphene, molybdenum disulfide, and other novel two-dimensional materials with desired physical and chemical qualities. The in-depth understanding of how to make those materials is enabling them to develop 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 investigated within those two areas:

- Chemical vapor deposition synthesis of heterojunctions of two-dimensional materials, such as metal semiconducting junctions (VS2–molybdenum disulfide);
- Selective synthesis of aligned semiconducting carbon nanotubes using an electric field;
- Investigation of porous nanowire filters for high-capacity air purification;
- Chemical vapor deposition synthesis of high-quality single crystalline graphene and hexagonal boron nitride and understanding of growth mechanisms; and
- Developing the synthesis of Janus two-dimensional materials (MoSSe and so on).

The Kong group had several interesting results during the past year. Members of the group found that monolayer graphene can be effectively used as a protective layer in low-temperature copper bonding to prevent the intermetallic compound formation. This result will be very useful to the semiconductor packing industry. Through a collaboration with Tsinghua University in China, they found a method that can twist the chirality of carbon nanotubes during the synthesis process via electric field switching. This method results in aligned single-walled nanotubes with 99.9% purity—but results can be improved even further. This is very promising for using semiconducting carbon nanotubes for semiconductor device applications and future computing. In addition, through a collaboration with Professor Rohit Karnik's group in the Department of Mechanical Engineering, Kong laboratory members have investigated graphene membranes for desalting and dialysis applications. Graphene-based membranes have shown more than 10 times higher permeation and similar selectivity when compared with commercial polymer-based membranes.

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 correlating phonon structures of solids to ion transport. She also works on applying fundamental understanding to the design of materials for oxygen electrocatalysis, carbon dioxide reduction, ion intercalation, and ion conductors in electrochemical/photoelectrochemical conversion and storage, including lithium ion batteries, flow batteries, metal–air batteries, proton exchange membranes, and solid oxide fuel cells.

Replacing organic liquid electrolytes with solid lithium ion conductors in lithium ion batteries can boost energy density and also increase battery safety. Current research and development of solid-state lithium ion batteries has been catalyzed by recent breakthroughs in solid lithium ion conductors that have ion conductivities rivaling that of conventional organic liquid electrolytes. However, known fast solid lithium ion conductors are not stable against lithium ion battery electrodes. No fast lithium ion conductor known to date is stable against positive electrode materials in lithium ion batteries. It is of great importance to design new lithium ion conductors that not only have high lithium conductivity but also are stable during battery operation. Increasing ion mobility and the stability of lithium solid conductors is not straightforward and progress in the past decades has been achieved primarily by trial and error.

Structural and chemical tuning via isovalent or aliovalent substitution of cations or anions in given structural families have led to a steady increase in lithium ion conductivity and recent discovery of superionic lithium ion conductors. Professor Shao-Horn's group has reported correlations between lattice dynamics and ion mobility or stability against electrochemical oxidation. The group's work has highlighted opportunities to search for fast, stable lithium ion conductors with a low lithium band center but high anion band center. With rapid advances in computational capability, these descriptors are likely to be used in high-throughput studies to screen not only lithium ion conductors but also other technologically relevant ion conductors such as oxygen or sodium ion conductors.

Photonic Materials, Devices, and Systems

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

Professor Marc A. Baldo was the director of the US 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. Traditional electronic devices rely on expensive and energy-intensive fabrication processes; devices that use excitons are much better suited to the large-scale production needed to manufacture enough solar cells to have a significant impact on the world energy supply.

Professor Baldo's research program centers on solar cells, light-emitting devices, and spintronic switches. A key research accomplishment of the past year was his group's demonstration of coupling between silicon solar cells and singlet exciton fission in the molecular semiconductor tetracene. Originally proposed by Dexter in the 1970s, this coupling promises to increase the maximum efficiency of silicon solar cells to more than 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 hafnium oxynitride. The mechanism is presently unknown and will be the subject of future work.

A second result was the stabilization of organic light-emitting molecules by tuning the excited state over its lifetime. The work is relevant to OLEDs, which are widely used for mobile displays. Unfortunately, the relatively short lifetime of blue OLEDs remains a challenge in many applications. Stability has been widely regarded as a daunting chemical problem that is specific to every potential combination of materials. Here, Baldo's group demonstrated that there are also general physical principles that determine the stability of OLEDs, and that stability can be engineered via the photonic design of devices. Fundamentally, the degradation rate is controlled by the energy density within a device. The key component is the lifetime of excited states, which is experimentally isolated and systematically varied, yielding a 1,000–fold improvement in photostability for a sevenfold change in exciton lifetime, corresponding to a nearly quartic dependence. The dominant role of exciton lifetime suggests that the performance of the best OLED materials can be improved by engineering the device structure for rapid extraction of the energy stored in excitons.

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

This year, a focus of Professor Bulović's group, in collaboration with Professor Moungi Bawendi's group in the Department of Chemistry, was the development of next-generation light-emitting diodes (LEDs) for display and lighting applications. Electrically driven quantum dot light-emitting devices (QD-LEDs) have evolved significantly since their initial demonstration in 1994; they are a promising candidate for display and solid-state lighting applications. However, the performance of QD-LEDs that are based on emitters without heavy metals is still much inferior to that of QD-LEDs using cadmium-based emitters. This situation is largely because the synthetic chemistry of the heavy-metal-free quantum dots is relatively undeveloped. In this work, the collaborators synthesized the zinc selenide/zinc sulfide core/shell quantum dot using a combination of hot injection and continuous injection methods (hot injection is used to synthesize the small seed particles and continuous injection is used to overcoat the small seeds with different compositions). The resulting highly crystalline and monodisperse zinc selenide/zinc sulfide quantum dots exhibit a high absolute photoluminescence quantum yield (greater than 80%) and a narrow emission linewidth (9 to11 nm, 70 to 90 MeV) with matching ensemble and single quantum dot emission linewidth. The use of zinc selenide/zinc sulfide quantum dots as emitters with a fully solution-processable method in an organic-inorganic hybrid device structure resulted in QD-LEDs with maximum luminance up to 100 candelas per square meter and a peak external quantum efficiency of 1.2%. The device exhibits a surprisingly narrow emission, with a full width at half-maximum of only 15 nanometers, which to the group's knowledge is the narrowest deep blue emission for QD-LEDs that has been reported to date. These findings indicate that heavy-metal-free blue quantum dots hold great promise for the development of next-generation LEDs for display and lighting applications.

Professor Peter Hagelstein's group continued theoretical and experimental studies related to condensed matter nuclear science, which includes cold fusion and a variety of related anomalies. In particular, the group looked at phonon-nuclear interactions and experiments to test phonon-nuclear coupling.

Phonon-nuclear Interaction

In the report for academic year 2017, Professor Hagelstein's group described new models for nonrelativistic and relativistic quantum composites, where they 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. In the group's view, this provides the underlying interaction Hamiltonian for the many anomalies that have been reported over the years.

In academic year 2018, the Hagelstein group made use of the interaction to develop a computation of phonon-nuclear coupling for the 6.237 kiloelectronvolts (keV) nuclear transition in tantalum-181 (^{181}Ta). This transition is singular within the theory because it is one of the very rare low-energy electric dipole transitions for stable nuclei (it is the lowest of them).

Researchers had proposed a Mossbauer experiment in the homonuclear diatomic molecule Ta_2, in which phonon-mediated coupling was expected to lead 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. There is now an estimate for the coupling matrix element, making it possible to evaluate the splitting; however, the splitting that is consistent with the estimate is too small to be observed.

Members of the Hagelstein laboratory have long been interested 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 is considered to be 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 such experiments permit an interpretation of nuclear excitation through the upconversion of vibrations. The Hagelstein group has been working toward the development of an experimental facility in which to test some of these claims, and also to test new experiments that the group has proposed.

Some years ago, the Hagelstein group worked with SRI to see if it was possible to observe X-ray emissions and charge emissions from a copper foil vibrated at approximately 20 MHz. The SRI team reported signals consistent with positive results for both effects, which was cause for some excitement. The Hagelstein team found, first, that the calibration of the X-ray detector was off; when it was corrected, the X-ray measurements were found to be artifacts. Subsequently, members of the team ran tests at MIT to see whether they could confirm the charge emission. They saw signals that were something like what had been reported at SRI, but when they tried to charge a capacitor with the associated charge, they were unable to get a voltage. The charge emission signal in the MIT experiment was an artifact. SRI carried out a similar test on its version of the experiment with similar results.

In the report for academic year 2016, researchers discussed a confirmation test for Kornilova's waterjet experiment, in which collimated X-ray emissions in the keV regime are claimed. Tests conducted this past year found several artifacts associated with pinholes and bent film, but no X-ray emission.

Phonon-nuclear coupling experiments began in spring 2018 with the various transducers and detectors described in an earlier RLE report. A test of upconversion in a steel plate that was vibrated near 100 watts around 2.23 MHz showed a variety of artifacts, but in the end produced a negative result. Researchers tried an excitation transfer experiment with a cobalt-57 source evaporated on a steel plate, in which they looked for a reduction in source emission on the 14.4 keV transition during vibrational stimulation. In the course of the experiment, a variety of artifacts were encountered, but 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_α and K_β. Based on previous experience, researchers suspected another artifact. However, in this case, the detectors appear to have functioned properly. It was not possible to reproduce the effect at the level first observed; however, it was possible to develop a weaker version of the effect in response to different stresses applied to the sample. The Hagelstein group has now seen non-exponential decay in six or seven runs, and has also seen evidence for the anomaly on three different detectors.

What researchers see is an enhancement of the 14.4 keV gamma and the Fe K_α and K_β x-rays. They may also be seeing a reduction of emission of the 122 keV and 136 keV gammas, but will have to have direct measurements to be sure. The enhanced emission on the surface seems qualitatively consistent with an upconversion effect, as described by the model that they are testing. However, at times where the enhancement is evident, there is no obvious source of high-frequency phonons to be upconverted, and the researchers have recently come to the conclusion that enhancement is not a result of the specific physics described by the model. Instead, probably what is needed is a new, closely related model in which the nuclear transitions are coupled to moving dislocations in the metal sample.

The enhancement is probably a result of stress-induced nuclear excitation. There are a number of experiments described in the literature that show related but different (nuclear) anomalies that are either a result of the application of stress to various samples, or else can be interpreted as being induced by stress.

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

Previous experimental research by other groups indicates that collimated X-ray emission is possible in this kind of experiment. The Hagelstein team has not tested for collimation. It may be that a much more mature version of the experiment could provide an X-ray source for applications in lithography.

Professor Qing Hu studies terahertz (THz) quantum cascade lasers and electronics, particularly sensing and real-time THz imaging using quantum cascade lasers and focal-plane cameras. His group has achieved a number of records in the performance of their THz quantum cascade lasers, including, but not limited to, the highest operating temperature in the pulsed mode (approximately 200°K without magnetic field and 225°K with magnetic field), and the highest operating temperature in the continuous-wave mode (117°K). They have performed real-time THz imaging at a video rate of approximately 20 frames/second. They developed a novel tuning mechanism that is qualitatively different from all other tunable lasers, and have achieved continuous tuning over a broad frequency range (approximately 330 GHz). More recently, they have 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.

Professors John D. Joannopoulos and Marin Soljacic work together as a team in the area of nanophotonics. They recently made a breakthrough discovery in the field of topological photonics, together with their former postdoctoral associate Bo Zhen, now a professor at the University of Pennsylvania.

Topological physics has found tremendous success in recent years, resulting in new physical insights and novel applications; the field was recognized by the 2016 Nobel Prize in Physics. However, previous work in this field was limited; physicists considered only Hermitian systems, whereas realistic physical systems, particularly in optics, naturally involve loss channels and gain. Professors Joannopoulos and Soljacic, with Bo Zhen, theoretically proposed, numerically designed, and experimentally demonstrated a novel system that, for the first time, extended topological band theory into the non-Hermitian regime. This led to the discovery of two new phenomena outside the scope of existing theories. First, they uncovered a fundamentally new type of topological degeneracy, possible only in non-Hermitian systems, that they called a bulk Fermi arc. Second, they demonstrated the existence of fractional topological indices in non-Hermitian systems, manifested as a half-integer winding of optical polarization—analogous to the orientation reversal on a Möbius strip.

This combined theoretical and experimental work presented a paradigm shift in topological physics and established a new and interdisciplinary area of research that bridges topological physics, non-Hermitian physics, and singular optics. This will stimulate synergies between these diverse fields and inspire future explorations of non-Hermitian topological physics in optical, electronic, acoustic, and polaritonic systems. From a technological point of view, the study also has many promising applications. Examples include topologically robust optoelectronic devices, high-power lasers with tailored emission profiles, and ultrafast low-power all-optical switches.

Professor Steven Johnson leads the Nanostructures and Computation Group. His research focuses on two areas; 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; and high-performance computation, such as fast Fourier transforms, solvers for numerical electromagnetism, and large-scale optimization.

The group made major progress in its continuing efforts to probe the upper bounds of light–matter interactions. In an August 2017 submission with Owen Miller at Yale to *Nano Letters*, they obtained the first theoretical upper bounds to absorption, scattering, and light emission by two-dimensional materials such as graphene. In a June 2018 *Nature Physics* article with Professor Soljacic, they obtained theoretical upper bounds to Cerenkov and Smith-Purcell radiation by free electrons, showed that existing structures fell far short of the upper limits, designed a new structure that comes close to the upper bounds, and experimentally validated the theoretical predictions. Their findings suggest that compact and efficient free-electron radiation sources from microwaves to the soft X-ray regime, for applications from imaging and spectroscopy to medicine, may be achievable without requiring ultrahigh accelerating voltages.

In a June 2018 *PNAS* article with Henry Everitt of Duke University, the Johnson group published important new theoretical and experimental results on an optically pumped far-infrared (OPFIR) laser, one of the most powerful continuous-wave THz sources for applications in imaging and sensing. Such lasers had long been thought to have intrinsically low efficiency and large sizes, and experiments disagreed with theoretical models at high pressures. In their new work, they showed the first theoretical model that correctly captured the experimental OPFIR behavior at high pressures, and experimentally demonstrated an OPFIR THz laser with 10 times greater efficiency and a thousand times smaller size than commercial THz OPFIR sources.

Professor Franz Kaertner's research focuses on the study of attosecond science, both in the gas phase and on an electronic-photonic chip. His group studied high-order harmonic generation with two-color laser fields together with Principal Investigator Kyung-Han Hong and carrier-envelope sensitive electronic devices with Professor Karl Berggren. Jointly with the Photonic Microsystems Group headed by Professor Michael Watts, Professor Kaertner's group attempted to integrate femtosecond laser technology on a complementary metal-oxide-semiconductor (CMOS) chip in a fully three-dimensional photonic-electronic integrated platform to enable advanced ultrafast optical signal synthesis and signal processing.

Researchers in the Kaertner laboratory continued to investigate ultrafast nanoplasmonic devices and their response to few-cycle optical fields. The field emission current from these devices shows a strong dependence on the carrier-envelope phase. They observed for the first time that this carrier-envelope phase-sensitive current shows nonlinear anti-resonant behavior as a function of field strength. For certain field strengths, the carrier-envelope phase-dependent current during different half cycles cancels. This defines a unique field strength for a device and can be used to determine the field strength in situ.

Led by Principal Investigator Hong, researchers performed high-order harmonic generation with a phase-locked two-color laser field based on the fundamental spectrum at 2.1 micron from a home-built optical parametric amplifier and its third harmonic at 700 nm. They showed, in agreement with theory, that high-order harmonic generation radiation can be enhanced with the two-color field in the plateau region. They observed up to one order of magnitude enhancement when compared with using only the fundamental laser field. In contrast with theory, they could not observe cut-off enhancement, that is, observing more energetic photons because of the use of the two-color driver field. More theoretical work and experimental work are needed to find out why this important aspect of multicolor laser fields is not observed.

Together with the Photonic Microsystems Group of Professor Watts leading the AIM effort, Hong's group has fabricated the first complete femtosecond lasers on a silicon photonics platform. The group participates in the Direct On-Chip Digital Optical Synthesizer Program sponsored by the Defense Advanced Research Projects Agency—a multimillion-dollar collaboration between MIT, the University of California, Berkeley, and the Colleges of Nanoscale Science and Engineering of the State University of New York. The goal is to enable self-referenced optical frequency combs and synthesis to join in a compact integrated package. After observing stable mode-locking with about 200-femtosecond double pulses at a 600 MHz repetition rate at the end of Phase I, MIT's team successfully entered Phase II of the DARPA Digital Optical Synthesizer Program. However, this performance was not reproducible; the high loss of the waveguides employed was found to account for this performance. MIT did not enter Phase III of the program, although the team received funding for an additional nine months (until the end of 2018) to find the cause of the high waveguide losses. Successful integration of femtosecond lasers on a chip has the potential to enhance a number of electro-optical systems such as optical frequency combs and synthesizers, high-speed photonically assisted analog-to-digital convertors fabricated by silicon photonic techniques.

Professor Rajeev Ram and the Physical Optics and Electronics Group pursued investigations in two major areas: integrated photonics and electron transport in semiconductors. Their 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 Michael Watts and his Photonic Microsystems Group have focused on three-dimensional integration of silicon photonics with CMOS electronics and on-chip lasers for a variety of applications. In particular, they are interested in ultralow-power wavelength division multiplexed optical communications, optical phased arrays, optical beam-steering, low phase noise optical-microwave oscillators, and microwave signal generation.

Principal Research Scientist Kyung-Han Hong of the Optics and Quantum Electronics Group in RLE is leading the development of novel strong-field ultrafast mid-infrared lasers and their applications to high-harmonic generation (HHG) for studying attosecond (10−18 seconds) science in gases and solids. He also participated in a project on compact X-ray light sources hosted by Arizona State University, where he contributed to developing highly stable high-power laser sources for inverse Compton X-ray generation. Hong and the group made progress in three subsidiary areas during academic year 2018:

Enhanced HHG up to the soft X-ray region using mid-infrared two-color (ω + 3ω) pulses: they systematically studied the efficiency enhancement of HHG in an argon gas cell up to the soft X-ray range, using a two-color laser field composed of 2.1 μm (ω) and its third harmonic, 700 nm (3ω). They observed suboptical-cycle-dependent efficiency enhancements of up to 8.2 of photon flux integrated between 20 and 70 electronvolts, and of up to 2.2 of photon flux integrated between 85 and 205 electronvolts. Enhancement of HHG efficiency was most pronounced for the lowest tested backing pressure and decreased monotonically as the pressure was increased. Numerical simulations performed by collaborators at Kansas State University showed good qualitative agreement with experimental observations. This systematic study revealed that the phase matching of two-color-driven soft X-ray HHG is more sensitive to the ionization rate and pulse propagation effects than single-color cases.

Long-wavelength-infrared (LWIR) intra-pulse difference-frequency generation: Hong's group developed a femtosecond, approximately 8.5 μm, approximately ~2 μJ source based on the intra-pulse difference-frequency generation (DFG) of 2.1 μm pulses in a silver selenogallate ($AgGaSe_2$ or AGSe) crystal, in collaboration with HiLASE in the Czech Republic. This was the first demonstration of intra-pulse DFG pumped at a wavelength as long as approximately 2 μm, providing efficient conversion into the wavelengths longer than 5 μm because of a lower quantum defect; this is more suitable for the non-oxide nonlinear crystals that have relatively low bandgap energy. Using femtosecond 2.1 μm pump pulses, researchers generated intrinsically carrier-envelope phase-stable idler pulses with a conversion efficiency of 0.8%, which covers the LWIR wavelength range of 7 to 11 μm. The simulation study showed that the blueshift of intra-pulse DFG is assisted by self-phase modulation of the driving pulses in silver selenogallate. The idler pulses are particularly useful for strong-field experiments in nanostructures as well as for seeding parametric amplifiers in the LWIR.

Highly stable, synchronized inverse Compton scattering laser: under the project with Arizona State University on compact X-ray light sources, Hong and his team developed a highly stable, high-power picosecond laser for driving inverse Compton scattering–based hard X-ray generation, which was optically synchronized to an ultraviolet photocathode laser that triggers an electron bunch. The inverse Compton scattering driver laser, a thin-disk ytterbium-doped yttrium aluminum garnet amplifier, generates 200 mJ, 1.1 ps, 1030 nm pulses at 1 kHz repetition rate with excellent shot-to-shot (0.52% rms) and long-term (0.14% rms of drift over 24 hours) energy stabilities as well as an excellent pointing stability. A highly stable photocathode laser is optically synchronized to the inverse Compton scattering laser with a timing jitter of 33 fs rms. The laser systems, demonstrated at MIT's Bates Research and Engineering Center, will serve as key components of the Arizona State University compact X-ray light sources user facility.

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 works on developing novel quantum devices and controls for them. In the past year, her group has developed quantum error correction schemes that can help quantum sensors achieve better precision. In addition, the group has devised a combinatorial sensor that exploits an ancillary quantum system to stabilize the primary quantum sensor, achieving stable measurements over hours, beyond what is possible with competing, MEMS-based sensors. This combinatorial sensor could be used to engineer a stable and robust spin gyroscope. Further improvements in the feedback-based stabilization protocol could be achieved by exploiting inference and machine learning techniques. Moving beyond the measurement of a single scalar field (parameter estimation), the group worked to develop an efficient method for quantum system identification (where all parameters of a quantum system Hamiltonian have to be revealed) and a scheme for vector magnetometry that does not require an ensemble of sensors, thus maintaining the high spatial resolution afforded by single quantum sensors.

A second area of research has focused on quantum thermodynamics, exploring quantum correlations influences on the precision of temperature sensing, and more broadly studying thermodynamic properties of many-body quantum systems out of equilibrium. In particular, exploiting Hamiltonian engineering techniques, the group explored the transition from a thermalizing system to a prethermal system, which displays quasi-conserved quantities at exponentially long times. Similar to localized systems investigated last year, these long-lived quantum systems are promising for quantum technology applications, such as quantum memories.

Professor Isaac Chuang's group studies theoretical and experimental quantum information science. They seek to harness the laws of quantum physics to solve hard problems faster than is possible with conventional classical computers.

Professor William D. Oliver, Research Scientist Simon Gustavsson, and Professor Terry Orlando direct a multi-university, multidisciplinary 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. The work is performed in close collaboration with Professor Oliver's team at MIT Lincoln Laboratory. In the past year, they focused on projects related to improving the connectivity and the readout of superconducting qubits.

Oliver, Gustavsson, and Orlando, in a project done in collaboration with partners at MIT Lincoln Laboratory, investigated the prospect of scaling up quantum computing to larger-scale systems using three-dimensional integration techniques. As the number of qubits on a chip becomes larger and larger, there will be increased difficulty in connecting the various qubits in a planar geometry, both in terms of control wiring and in terms of qubit readout. In this work, which was published in *npj Quantum Information*, they demonstrated the operation of a device where the qubits are manufactured on one chip and the control circuitry is located on a separate chip mounted just a few micrometers from the qubits. They were able to show qubit performance that was comparable with that of devices manufactured on just one chip, demonstrating that it is indeed possible to use three-dimensional integration to control and connect a large number of qubits.

The state of a superconducting qubit is typically determined by shining microwave photons onto them and looking for changes in the reflected or transmitted signal. However, the interactions with microwave photons also lead to back-action on the qubits, leading to decreased lifetimes and loss of quantum coherence. If residual photons are present in the system, they will negatively affect the performance of a quantum computer. These unwanted photons originate from a variety of sources, such as thermal radiation, leftover measurement photons, and measurement cross talk. Last year, Oliver, Gustavsson, and Orlando investigated the effect of radiation from different types of photons and found that the performance of the qubits was mainly limited by thermal radiation. Equipped with this knowledge, the improved the cryogenic filtering and successfully suppressed residual thermal photons to improve the qubit coherence time by a factor of two.

In the laboratory of Oliver, Gustavsson, and Orlando, and elsewhere around the world, there has been tremendous improvement in coherence times and 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, they see an opportunity for university growth in a new discipline—quantum engineering.

In addition, Professor Oliver has partnered with MIT's Office of Digital Learning to create a number of online professional development courses delivered via MITx Pro. The courses target different areas of quantum computing and quantum communication and include Introduction to Quantum Computing; Quantum Algorithms for Cybersecurity, Chemistry, and Optimization; and Practical Realities of Quantum Computation and Quantum Communication.

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. In the past year the group made several significant achievements. They continued their development of floodlight quantum key distribution, a novel method for securely distributing encryption keys that overcomes channel loss to achieve a gigabit per second key generation rate that is suitable for practical encryption of large files. In particular, they upgraded their experimental setup and demonstrated floodlight quantum key distribution operation at 1.3 gigabit per second secret-key rates, as reported in a recent paper in *Quantum Science and Technology*. This demonstration was made in a table-top experiment that employed channel attenuation equivalent to a 50-km-long optical fiber connection. They are exploring the possibility of performing future experiments on the 40-km optical fibers that link the MIT campus with MIT Lincoln Laboratory.

A second area in which the Shapiro and Wong group scored an important achievement this year was the demonstration of an unprecedented state purity of 99.7% for single-spatiotemporal-mode photons obtained by interfering two heralded single photons. By carefully controlling the Gaussian transform-limited pulsed pump and spectrally engineered spontaneous parametric downconversion in a periodically poled potassium titanyl phosphate crystal, they have now refined their technique of generating spectrally unentangled biphotons, which yields the high-purity heralded single photons. The technique can be particularly useful in measurement-based quantum photonic applications such as boson sampling, entanglement swapping, quantum repeaters, and the generation of heralded entangled photon pairs.

They also made two important advances relating to all-optical quantum computation. Both presume that continued progress in increasing the efficiency of second-order three-wave mixing processes, such as spontaneous parametric downconversion, will lead to fully quantum interactions of this type. Under that assumption, they have shown in a recent *Physical Review Letters* paper how universal quantum computation can be realized using only linear optics and three-wave mixing processes, in any $(n + 1)$–dimensional qudit basis of the n-pump-photon subspace. Building on the preceding result, they constructed three families of hardware-efficient quantum error-correcting codes whose encoding and decoding operations can be achieved with only linear optics and three-wave mixing processes. As demonstrated in a recent *Physical Review A* paper, all of these codes protect against photon-loss errors, which is the predominant error mechanism in all-optical quantum computation. Moreover, their most powerful code can correct m-photon-loss errors using logical qudits that are encoded in the order of N ($O[N]$) photons, whereas all other bosonic quantum error-correcting codes with this capability require $O(N^2)$ photons. Furthermore, their code constructions rely on a symmetry-operator formalism that establishes a systematic framework for finding new quantum error-correcting codes for available measurement schemes and physical subspace choices.

Personnel

Professor Dennis Freeman was appointed to the Henry Ellis Warren Chair in Electrical Engineering. The Warren Chair is designated for "interdisciplinary research leading to application of technological developments in electrical engineering and computer science, with their effect on human ecology, health, community life, and opportunities for youth." It was established in memory of Henry Ellis Warren, who was one of the Institute's first graduates in electrical engineering. Warren was best known for the invention (among his 135 patents) of the electric clock and its associated self-starting synchronous motor. He was also noted for convincing power companies to more tightly regulate the frequency on their nominally 60 Hz waveform, which eventually allowed the interconnection of regional power systems to form today's continental-scale power grids.

Professor Jongyoon Han was appointed to the 2018 Singapore Research Professorship for the MIT Singapore-MIT Alliance for Research and Technology Program.

Professor Thomas Heldt was promoted to the rank of associate professor without tenure in the Department of Electrical Engineering and Computer Science in July 2017. He was also appointed a visiting professor at ETH Zürich.

Professor Steven Leeb was appointed to the position of associate director of RLE in October 2017, aiding RLE in the pursuit of charitable gifts for laboratory renovations.

Professor Joel Voldman was appointed to the position of associate head in the Department of Electrical Engineering and Computer Science in September 2017.

RLE Headquarters hired three people this year. Cindy Matheson became senior fiscal officer, Kenny Luu was hired as assistant fiscal officer, and Michael Abramo joined RLE as administrative assistant II. Melissa Sheehan was promoted to manager of fiscal administration, Stephanie Muto was promoted to assistant fiscal officer, and Sampson Wilcox was promoted to senior web and media designer. Nan Lin (senior fiscal officer) left RLE to become administrative officer for the Department of Mathematics.

Faculty Honors and Awards

Professor Polina Anikeeva was awarded a 2018 Vilcek Prize for Creative Promise in Biomedical Science in April 2018.

Professor Luca Daniel was among the authors of a paper that appeared on the cover of the *Journal of Magnetic Resonance in Medicine* in November 2017. He also received the *IEEE Transactions on Components, Packaging, and Manufacturing Technology* award for Best Journal Paper in the year 2018.

Professor Yoel Fink was recognized by *Science* for the creation of the Translational Fellows Program.

Professor Dennis Freeman received the Burgess and Elizabeth Jamieson Award for Excellence in Teaching and the Innovative Seminar Award for Excellence in Freshman Advising.

Professor James Fujimoto received an honorary doctorate from the Fredrich Alexander University of Erlangen, Nürnberg, Germany.

Professor Muriel Médard received the IEEE Edwin Armstrong Award and the Association for Computing Machinery Special Interest Group on Data Communication Test of Time Award.

Professor David Perreault received two awards in September 2017: the *IEEE Transactions on Power Electronics* First Prize Paper Award for "A Systematic Approach to Modeling Impedances and Current Distribution in Planar Magnetics," and the IEEE Energy Conversion Congress and Exposition TC6 Paper Award for "Dynamic Matching System for Radio-Frequency Plasma Generation," published in *IEEE Transactions on Power Electronics*, March 2018.

Professor Vivienne Sze received two awards in 2018: the Custom Integrated Circuits Conference Outstanding Invited Paper Award and the Qualcomm Faculty Award. She was also a member of the Joint Collaborative Team on Video Coding, which developed the acclaimed high efficiency video coding standard. For its work, the team received an Engineering Emmy Award during the Television Academy's recent 69th Engineering Emmy Awards ceremony in Hollywood, CA.

Professor Yang Shao-Horn was elected to the National Academy of Engineering in 2018, received the Royal Society of Chemistry Faraday Medal in 2018, was elected a fellow of the Electrochemical Society in 2018, and was on the Thomson Reuters Highly Cited list in 2017.

Principal Research Scientist Stefanie Shattuck-Hufnagel was elected to the executive board of the Association of Laboratory Phonology.

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

Professor Martin Zwierlein was awarded the I. I. Rabi Prize in Atomic, Molecular, and Optical Physics with the American Physical Society in 2017.

Staff Awards

A number of RLE community members won the 2018 Infinite Mile Award under the Office of the Vice President for Research. They were Molly Kruko, administrative assistant for Professor Muriel Médard, Professor Yoel Fink, and Professor Lizhong Zheng; Laura von Bosau, administrative assistant for Professor Jeffrey Grossman; and Flor Nawara, senior human resources representative in RLE headquarters.

Student Awards

Wei Ouyang, a student in the Department of Electrical Engineering and Computer Science, supervised by Professor Jongyoon Han, was awarded the 2018 Peake Research Prize. Ouyang is recognized for his work on an entirely new way to detect biomolecules (DNA and proteins) and cells in a complex sample such as blood, which is crucial in many disease diagnostics. He is engineering a highly efficient molecular/cellular concentration system that can collect low-abundance biomolecules and cells from a larger volume (greater than one milliliter) and put them into a much smaller volume (approximately one picoliter), increasing the effective concentration of those molecules significantly (an increase of a millionfold to a billionfold). This allows them to be accurately analyzed. Ouyang is applying this technique to detecting blood-borne pathogens (to indicate sepsis), to diagnose tuberculosis, and to many other biomedical sensing applications.

Emily Toomey, supervised by Professor Karl Berggren, was awarded the 2017 Ernst A. Guillemin Thesis Award for best electrical engineering master's thesis in the Department of Electrical Engineering and Computer Science. Toomey's thesis, "Microwave Response of Nonlinear Oscillations in Resistively Shunted Superconducting Nanowires," describes her work on studying the control of thermal behavior in superconducting nanowires through resistive shunting. In particular, it investigates how the resulting high-frequency relaxation oscillations interact with an external drive to produce behavior conventionally associated with Josephson junctions.

Affirmative Action and Outreach Activities

RLE has worked, and will continue working, to increase the number of women and members of minority groups in career positions in the laboratory. Professor Farnaz Niroui will be joining us as a junior faculty member in November 2018. During academic year 2018, RLE hosted Professor Anita Hill, a law professor from Brandeis University, on her sabbatical as a Martin Luther King scholar. She led a successful speaker series to engage and educate MIT and the Boston area on the role of Title IX in education, particularly education in science, technology, engineering, and mathematics. Known as the Gender/Race Imperative, the program sought to revive awareness of the broad capacity of Title IX and to promote inquiry to foster legal, policy, and social reforms that enable success in schools and workplaces for girls and women of all races and economic backgrounds. Professor Hill's work at MIT brought engineers, students, administrators, and other scientists to conversations with lawyers and social scientists to develop multidimensional strategies for promoting equity in science, technology, engineering, and mathematics.

RLE continues its work in nurturing future generations of engineers and scientists. Again this year, the Center for Ultracold Atoms conducted a program to bolster 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, 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 Teaching Opportunities in the Physical Sciences 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 students traveling from other states to take part. This was the 13th year in which the Center for Ultracold Atoms ran the program.

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

Marc Baldo
Director, Research Laboratory of Electronics
Professor of Electrical Engineering and Computer Science