Research Laboratory of Electronics

The Research Laboratory of Electronics (RLE) at MIT is a vibrant intellectual community and was one of the Institute's earliest interdepartmental academic research centers. The mission of RLE is furthering scientific understanding and leading innovation to provide service to society. RLE research spans basic science and engineering across an extensive range of natural and man-made phenomena. The lab harnesses expertise in fields as diverse as quantum physics, information theory, synthetic biology, and power electronics. We synthesize these disciplines for the benefit of applications in communication systems, energy transduction, computation, and innovations in diagnostics and treatment of human diseases.

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

With a research volume of $46.756 million in fiscal year 2019, the lab continues to be one of the Institute's leading research organizations. RLE manages more than 200 active research projects and services for over 70 principal investigators (PIs). In fiscal year 2019, 250 graduate students and 85 undergraduates worked in various labs.

Since 2011, RLE has been endowed primarily by royalties from high-definition (HD) TV intellectual property developed by lab researchers. The proceeds of this endowment are the basis for RLE's discretionary activities and budget. Major research funding is provided by Department of Defense agencies, the National Science Foundation (NSF), the National Institutes of Health, and the Department of Energy (DoE). Additional funding is provided by 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

The 2018–2019 academic year saw many awards, recognitions, and milestones for RLE investigators. The following is a summary of RLE research highlights from the past year.

Atomic Physics

Research in atomic physics at RLE encompasses investigations in ultra-cold atoms, quantum condensed gases, and atom optics. New methods are being developed for manipulating and probing Bose-Einstein condensed atomic gases and exploring ultra-cold interactions and collision dynamics in bosons and fermions. Additional work focuses on atom lasers, atom interferometry, atom waveguides, surface physics, and many-body physics in lower dimensions, plasmas, and electromagnetics.

The research of Professor Wolfgang Ketterle focuses on many-body physics with ultra-cold atoms and molecules. A major goal is to assemble these building blocks into new materials and study their properties.

During the past year, Ketterle and his group demonstrated how the combination of oscillating magnetic forces and radio frequency (RF) pulses endows RF photons with tunable momentum. When RF transitions between two different hyperfine states occur in the presence of an alternating magnetic field gradient, the time-averaged evolution is an RF transition where recoil momentum is transferred. The sign and magnitude of the momentum kick are adjustable via the magnetic fields, and the group observed a recoil momentum for the dressed photon that was 6 million times higher than the (usually negligible) momentum of a bare RF photon.

In the field of ultra-cold molecules, the group was able to realize collisional cooling of molecules for the first time. This was done in the form of sympathetic cooling of NaLi molecules (in the triplet ground state) by Na atoms. Evaporative cooling of Na lowered the temperature of NaLi molecules and increased the phase-space density by a factor of 20. Spin alignment of Na and NaLi was critical in suppressing inelastic collisions.

The research of Professor Vladan Vuletic focuses on large quantum mechanical systems and how quantum correlations (entanglement) can be used to perform tasks that are impossible within classical physics. A particular focus is on how to use quantum correlations that are stronger than classical correlations to improve atomic clocks and atomic interferometers, to enable quantum computation, and to control photons individually. In terms of recent highlights, the Vuletic group has demonstrated a programmable quantum simulator with up to 51 individually controllable quantum bits and the largest maximally correlated states with 20 qubits. In addition, they have provided a demonstration of entanglement to improve atomic clocks and the first demonstration of repulsive interactions between individual photons.

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

A highlight over the past year has been the Zwierlein group's work on boiling a unitary Fermi liquid. Fermi liquids rely on the presence of a Fermi surface—a well-defined boundary separating states that are filled with and those that are void of fermions. However, very little is known about what happens when Fermi liquids are heated. The group managed to study this question quantitatively in their atomic Fermi gas with the help of RF spectroscopy. At low temperatures, the gas contained well-defined quasi-particles—bare particles "dressed" by their fermionic environment—as expected for a Fermi liquid. However, as temperatures were increased to about the Fermi temperature of the system, the spectra broadened to a width on the order of the Fermi energy, as quasi-particles ceased to exist. This quantum critical regime is central to current understandings of high-temperature cuprates. At high temperatures, the group recovered the classical Boltzmann regime of particles scattering with a cross section as large as allowed by quantum mechanics.

In addition, the group performed a complementary study of the fate of impurities strongly interacting with a Bose-Einstein condensate. They observed a breakdown of the quasi-particle picture at elevated temperatures and a linear increase in the decay rate of quasi-particles with increasing temperatures, a telltale sign of quantum criticality.

With experiments on strongly interacting fermions and Bose-Fermi mixtures, we are entering an era in ultra-cold atoms 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 theme comprises work in power electronics, signal-level control circuits and electronics, system identification and control, continuum electromechanics, and high voltage and insulation research.

The work of principal research engineer Chathan Cooke, a member of the Laboratory for Electromagnetic and Electronic Systems (LEES), is mainly directed in three areas: resonant magnetic power transfer, magnetic induction undersea communications, and energetic electron/photon beam interactions.

With respect to resonant magnetic power transfer, Cooke and his graduate student Daniel Schemmel from the Department of Electrical Engineering and Computer Science (EECS) have been using a combination of detailed modeling and experiments to validate a complete "wire-to-performance" simulation model that accurately determines performance efficiency for a given set of windings and their configuration. This work, which is supported by an industrial sponsor (Prolec-GE), is primarily applied to improving electronic transformers. The modeling includes losses due to skin and proximity effects and has been validated for frequencies to 300 kHz. Models and experiments up to the 1 kW level demonstrate that high power transfer efficiencies of more than 95% can be achieved.

The magnetic induction communications work has been performed in collaboration with the MIT Sea Grant College Program. Cooke and his EECS graduate student Aaron Rose (along with MIT undergraduate Emanuel Perez) have developed broadband magnetic sensors and magnetic induction transmission with the goal of enabling undersea communications to convey data from underwater sensors to an autonomous surface vehicle. Dock-side tests have confirmed theory and experiments related to magnetic communication signal strengths. One planned example of the technology is to apply it to monitoring ocean condition dynamics near commercial fishing grounds to better understand the impact of ocean warming. A demonstration underwater data collection system for use with underwater communications is under construction.

Electron and photon beams for energetic radiation work are produced by the Van de Graaff accelerator facility in the Building N10 High Voltage Research Lab. In collaboration with the Harris Orthopedic Biomechanics and Biomaterials Laboratory at Massachusetts General Hospital (MGH), these beams have been applied to develop improved durability of materials for hip and knee implants. Also, in work with satellite instrument companies, the beams have been used to calibrate various satellite solar flux detectors. Moreover, they have been applied to basic physics studies performed by Professor Richard Milner and his graduate student Charles Epstein, and this work is the first to quantify the Moller effect at energies below 10 MeV.

The resonant magnetic power transfer work provides an opportunity for new methods to transfer energy from different types of power sources (e.g., photovoltaic, wind) to the traditional power grid. This work provides a great example of how basic electromagnetic principles can be applied to yield improved practical devices with global applications.

The ability to communicate over moderate distances, to about 1 km, is useful for modern sensing and opens the way for new understandings of ocean dynamics, especially as ocean temperatures alter the seascape. It also may become valuable for divers as a reliable means to communicate with the surface.

The biomaterials work is particularly interesting since it offers the opportunity for very durable long-life implants such as hip joints. The possibility of extending these surgically implanted materials to injectable materials is intriguing since it would reduce the costs and hazards associated with full surgical implants. The basic electron particle physics work is also exciting as it provides a new understanding of energetic particle interactions. The ability to use electron beams to investigate new sensors for solar flux measurement is even more important as sun-earth interactions take on new urgency.

Professor James Kirtley of LEES is a specialist in electrical machinery and electric power systems. Over the past year, his group has made progress in a number of different areas.

The collaborative effort with Mohamed Al Hosani of the Masdar Institute of Science and Technology in Abu Dhabi and Professor Konstantin Turitsyn of the Department of Mechanical Engineering at MIT has concluded. Graduate student Po-Hsu Huang has extended the stability criterion to multiple inverters, allowing a description of ways of stably operating microgrids dominated by inverter-based sources using master/slave or multiple droop characteristics. Graduate student Edwin Fonkwe has developed detailed simulation models for microgrids dominated by engine-based generation and shown how to use those models in real-time simulation boxes based on field-programmable gate arrays. The work is continuing under a new project with the Masdar Institute, now part of Khalifa University. This project focuses on space systems and involves four faculty members at Khalifa (Hatem Zeineldin, Mohamed Shawky el Moursi, Vinod Khadkikar, and Mohamed Al Hosani) and three at MIT (Steven Leeb, David Perreault, and James Kirtley). A three-inverter microgrid experiment has confirmed the results of Huang's work.

The Magna International project, which focuses on designing improved drive motors for battery electric vehicles, has resulted in designs of surface-mount permanent magnet motors, radial flux induction motors, and permanent magnet assisted synchronous reluctance motors. All of these designs appear to be valid solutions to electric car propulsion. Design selection will be determined by the cost and availability of permanent magnet materials. Stephen D. Umans has rejoined Professor Kirtley's group and is contributing his expertise in numerical analysis to the effort. Ways of evaluating motors over useful drive cycles have been developed, including a clustering method to evaluate motor efficiency with a small number of representative operating points.

A collaborative project with the Tata Center for Technology and Design has led to a better understanding of why batteries fail. As part of the project, which focuses on storage batteries used in direct current (DC) microgrids in remote, non-grid-connected areas, graduate student Rakesh Kumar has developed a control device to better monitor and promote the health of batteries. The work is continuing with two Undergraduate Research Opportunities Program (UROP) students.

With sponsorship from the Office of Naval Research, RLE research specialist William Lynch is developing an experimental setup involving lithium- ion cells to understand their dynamic performance and enhance their use for pulsed power applications on navy ships. Methods of cell balancing are being developed in collaboration with this work.

Professor Jeffrey Lang's research generally focuses on electromagnetic and electromechanical energy-conversion, motion-control, and sensing systems. Its applications involve, for example, the analysis, design, and control of high-performance electrical machine systems, energy harvesters, micro/nano-scale electromechanical actuators and sensors, and/or distributed electromechanical structures.

The processing of information by computers and other digital hardware is consuming ever-increasing amounts of energy. To reduce the energy used and, thus, decrease waste heat and extend the battery life of hand-held hardware, lower-voltage (and hence lower-power) digital switches are desired. Over the past few years, Lang and his group have developed a nanoelectromechanical relay, or switch, that appears capable of operating at voltages well below those used to operate the common transistor switch. The active part of the relay is a tunneling gap that is held together by a thin compressible molecular film. Electromechanical compression of the gap, so as to vary its separation, regulates the tunneling current through the gap. During the past year, the group has explored the behavior of the relay as the molecular film is varied. They have demonstrated that different films involve different switching speeds and voltages as well as different fabrication and aging characteristics. Thus, they have identified engineering the molecular film as a critical activity along the path of relay development. In addition, they have demonstrated that the relay is a very useful tool with which to measure the combined electrical and mechanical properties of thin molecular films. The relay offers metrology opportunities not previously available and therefore could have applications outside the world of digital switching.

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. RF energy harvesting (i.e., harvesting of energy from ambient radio signals) is a much-lower-power alternative that could be used to power a wide variety of autonomous wireless sensor nodes. This past year, the group demonstrated an RF energy harvester fabricated entirely from carbon nanotubes. Carbon nanotube–based transistors show great promise as the building blocks of wireless sensor nodes because they can be used to build three-dimensional (3D) circuits. This makes it easier to combine a large number of sensors and their associated signal processing, memory, and communication into a very small package. Of course, such sensing systems require power, and as autonomous devices their power source must be self-contained. The group's work has demonstrated that at least one power supply alternative, namely RF energy harvesting, can be manufactured from the same carbon nanotubes as the sensing system.

Professor Steven Leeb and his Electromechanical Systems Group harness energy conversion processes. The group is interested in attacking any engineering problem whose solution will enhance quality of life, improve the efficiency and performance of a useful electromechanical process, or minimize the environmental impact associated with electromechanical energy conversion. Members of the group design and apply embedded control systems, power electronic circuits, power systems, analog and digital circuits, and new materials for sensors, actuators, and power production.

Professor Leeb's group has had an extraordinary year developing systems for controlling and generating energy. Specifically, Professor Leeb and his team have:

- Co-invented and obtained a US patent for a new power electronic circuit that minimizes the need for energy storage in a power electronic converter by dynamically reconfiguring capacitive storage to ensure unprecedented utilization of stored electrical energy.
- Overseen the application of a $5 million grant from T.J. Rodgers for the construction of a new electronics prototyping laboratory that will serve all of RLE when construction is complete in summer 2019.
- Assisted in the development of start-up laboratories for new RLE faculty hires.
- Developed new mathematical techniques for nonintrusive electromechanical diagnostics. Specifically, the nonintrusive load monitoring (NILM) system and the NILM dashboard prevented an engine room fire on a serving warship in the US Coast Guard. A graduate student in Professor Leeb's group received a commendation from the Coast Guard's chief engineer for this work. News coverage of the success was presented on the MIT splash page, in *Scientific American* online, and elsewhere.
- Further developed a new technique for detecting instability on DC microgrids and new power electronic control technologies for automatically remediating or avoiding instabilities.

Professor David Perreault's research focuses on advancing power electronics technology and using power electronics to benefit key applications. Major research thrusts include the development of extreme high-frequency power conversion to attain miniaturization and integration and the use of power electronics for applications such as solar photovoltaics and transportation.

One area of success this year has been the development of improved approaches for high-frequency power magnetic components. This includes the investigation and development of a new structure for inductors to achieve high efficiency at high frequencies (3–30 MHz), work that has led to one conference paper and one journal paper, with another conference paper submitted. This magnetic structure is also a key element in a new grid interface power converter design operating at extremely high-power densities while maintaining high efficiency. A further area of success has been the development of customized power converters to support new applications, including the creation of an extremely miniaturized multi-input single-output converter enabling panel-integrated, laterally arrayed multi-bandgap photovoltaic cells. This work is the topic of two conference papers and a submitted journal paper. Another example is the development of an ultra-light-weight, high-voltage (200 V to 40 kV) DC-DC converter for electroaerodynamic propulsion and associated new design techniques. This work has been described in two conference papers, a journal paper submitted for publication, and a *Nature* paper describing the first flight of an airplane with solid-state propulsion.

The research of Professor David Trumper, a member of LEES, is focused on precision mechatronics applied to a wide range of problems from health care to precision manufacturing. Over the past year, Professor Trumper and his group have worked on six major projects:

- The group has continued 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. The 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 Griffith, the group has been designing mechatronic solutions for novel multi-organ human tissue bioreactors. This research is leading to the creation of new microphysiological systems for in vitro studies of human organ tissues such as brain, gut, and liver cells. The group is working toward a demonstration of new results for brain/gut/liver interactions.
- In another collaboration, with Professor Griffith and Professor Rebecca Carrier of Northeastern University, the group is designing mechatronic solutions for microphysiological systems that will allow studies of human gut behavior in the presence of gut bacteria as well as gut/liver interactions. As part of this effort, the group has designed new types of platform mechatronic flow configurations and new electromagnetic actuators for highly power-efficient microfluidic pumping.
- Professor Trumper is 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 enables the next step of testing on animal subjects. Trumper plans to work with his industrial partner to apply for a Small Business Technology Transfer Phase II effort aimed at creating a working product for human use with a focus on pediatric patients.
- In a completed collaboration with the Masdar Institute, the group designed new approaches for solar energy collection and storage in a molten salt system. Several papers on this work have been submitted to conferences and journals.

- In a collaboration with Lincoln Laboratory, the group is designing a new type of momentum wheel for microsatellite attitude control. This design has successfully demonstrated one-axis levitation and is currently being configured for full three-axis levitation and three-axis angular momentum control. The group is also working with Lincoln Lab to secure funding for the design and testing of a flight-qualified unit.

Information Science and Systems

Research in this area spans a complete range of activities over all aspects of electronics, including structures, devices, and circuits; analog and digital systems; microelectromechanical systems (MEMs) and bioMEMs; nanotechnologies; numerical and computational simulation and prototyping; biologically inspired systems; digital signal processing; advanced telecommunications; medical imaging; and exploration of fundamental issues in wireless networking and devices.

This year, research in Professor Vincent W.S. Chan's group has focused on three main areas: cognitive management and control for wavelength assignment and reconfiguration in optical networks, diversity routing to improve delay-jitter tradeoffs in uncertain network environments, and IoT/smart cities networks.

In research on cognitive management and control, the group is addressing the design of a fast-response algorithm for wavelength reconfiguration. Two Bayesian estimators and a stopping-trial sequential estimator have been developed to detect changes in traffic arrival statistics. First, based on the transient behaviors of the network, the group has shown that the stopping-trial estimator has the shortest detection time for traffic rate changes and requires no knowledge of a priori probabilities. Second, the continuous assessment enables the system to reconfigure only when necessary and compensate for the estimator's detection inaccuracy. Finally, the stopping-trial estimator requires only a small number of wavelengths to be reconfigured due to its fast response.

The group's cognitive wavelength assignment and reconfiguration design provide efficient and simple-to-implement architectures that can avoid network management and control burdens, thus improving the cost efficiency of large dynamic transactions. This is extremely important for the network in terms of stability, scalability, reliability, and evolvability. With the fast dynamics noted, an agile cognitive optical network management and control system will guarantee both quality of transmission and network robustness with little or no involvement of humans. These advancements make it more affordable for the network to meet changing requirements and incorporate new technology. This work won a best paper award at the IEEE (Institute of Electrical and Electronics Engineers) International Conference on Communications.

With respect to diversity routing, the group has introduced a new mechanism for efficient allocation of traffic across a diversified set of paths. This allocation allows the network to deliver customizable service quality to different users and reduces the need for buffers at various network elements. The group's work focuses on the tradeoff between mean delay and jitter as the main contributors to service quality. An important feature of this approach is its capacity to achieve desired service quality despite the relative uncertainty about the state of the network. Noting that the introduction of demanding applications often outpaces that of network upgrades, Chan and his group have argued that their innovative solution can accelerate adoption of these applications without the need for immediate capital expenditures. They have extended their findings to general transportation networks and argued that their approach can significantly improve supply chain predictability and reduce the need for storage facilities. A provisional patent has been filed, and a full patent will be filed by early fall.

The group completed a detailed architecture description for a baseline IoT/smart cities network. The new architecture framework involves major changes with respect to the current architecture to take into account IoT requirements and characteristics including energy efficiency, interference mitigation, cross-layer protocols (to account for differences in latency and reliability requirements among different applications), device mobility, and the impact of the "coherence time" of network dynamics. New resource allocation algorithms for heterogeneous communication systems have been devised. Work completed thus far includes:

- Development of a smart cities network model that takes into account surges and time-critical latency requirements from applications. This work highlights the necessary network characteristics and the resulting infrastructure.
- Construction of an architecture for priority access at the network edge that includes random access for service reservations with cognitive network tuning algorithms.
- Creation of priority access schemes for the metro area network to provide time-critical services such as autonomous vehicle safety. This work included router service requirements and modeling and access network physical topology with agile cognitive tuning.

The architecture constructed is very different from current 5G (fifth-generation) constructs. Chan and his group expect that many of these features will be part of the future evolution of 5G.

The Energy-Efficient Circuits and Systems Group, led by Professor Anantha Chandrakasan, investigates new circuit-level and architectural techniques to enable improvements in energy efficiency and security for a wide range of integrated electronic systems. Example application domains include security, energy harvesting and wireless charging for the Internet of Things (IoT), multimedia processing, and biomedical electronics. One highlight from the group this year was a collaborative project on a gastrointestinal (GI) sensing platform with RLE professor Tim Lu (who co-led the project) and his student Mark Mimee. In addition, Giovanni Traverso and Professor Robert Langer's group in the Koch Institute for Integrative Cancer Research, as well as Professor Vladimir Bulović's group in RLE, were 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 diseases. Unfortunately, sensing molecules in the gastrointestinal tract is challenging due to its caustic environment and relative inaccessibility.

In recent work published in *Science*, Professor Chandrakasan and his team succeeded in demonstrating an ingestible biosensor based on engineered bacterial cells, believed to be the first time that living cells have been used for real-time chemical sensing in the gut. Cells are naturally adept at sensing molecules present in their surroundings and naturally resilient to many challenging environments, including the GI tract. In the group's proof of concept, 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 their fluidic surroundings via a semipermeable membrane. Upon exposure, the cells signaled the in-capsule circuitry through luminescence, and the capsule transmitted the measured luminescence levels wirelessly to a nearby laptop or smartphone.

While the immediate potential application for this work is as a monitor for upper gastrointestinal bleeding in patients at high risk for variceal bleeding, the group anticipates that the platform will be modular and that it can be made to sense other molecules by engineering new cellular sensors. Future work will focus on developing new sensors and proving them in animal models, as well as reducing the size of the ingestible capsule in order to lower the probability of complications.

The research group of Professor Luca Daniel develops algorithms and computing tools related to integral equation solvers, parameterized model order reduction, uncertainty quantification, inverse problems, and robust optimization. Applications of the group's computing techniques include silicon photonics, magnetic resonance imaging (MRI) scanners, and robustness quantification for deep neural networks. Recent research highlights are described below.

The group has developed a new algorithm for the computation of a singular value decomposition (SVD) low-rank approximation of a matrix in the matrix product operator format, also called the tensor train matrix format. Their approach is 10 times faster and has the same or better accuracy than the state-of-the-art tensor-based alternating least squares SVD and modified alternating least squares SVD matrix approximation methods. In addition, their algorithm produces accurate approximations in cases where all of the state-of-the-art approaches fail to converge. They have also proposed a new algorithm for fast conversion of a sparse matrix into its corresponding tensor train matrix form that is 500 times faster than the standard tensor train SVD method while achieving machine precision accuracy.

Daniel and his group have shown how arrays of coupled resonant oscillators can provide wildly disordered phase responses corresponding to non-synchronized regimes. The unpredictability of their time response makes oscillator arrays attractive randomness sources for cryptographic applications. The group has developed a possible implementation of a random number generator combining their randomness source with a few low-cost elements needed for bitstream generation. Several bitstream sequences have been simulated with a numerically efficient phase-domain model capable of including oscillator phase noise and parameter variability. The randomness of the generated bitstreams has been verified using tests provided by the National Institute of Standards and Technology. The group's results show that the statistical properties of their random number generator are indeed resilient to temperature-induced thermal noise variations as well as to the statistical uncertainty of oscillating frequencies and coupling strengths.

The research focus of Professor Alan Oppenheim and the Digital Signal Processing Group includes exploration of new algorithms for signal processing and related applications. Over the past year, they have completed a number of projects in signal sampling and signal detection and have begun new projects in detection, estimation, and processing in the context of quantum environments. These newer projects tie back in part to their much earlier work on quantum signal processing and also exploit their recent work on classical detection and receiver operating characteristics (ROCs). Their most interesting results on classical signal sampling relate to the development of a new concept that they refer to as amplitude sampling and its generalization to lattice sampling. Such concepts have important implications in data acquisition and analog/digital conversion. Their recent results on classical ROC curves as they are used in clinical data analysis, signal detection, and machine learning suggest ways of potentially improving test design and the performance of empirically obtained ROC curves.

The group's research on quantum signal detection, estimation, and processing is in its very early stages and is currently oriented toward exploring novel ways of utilizing the connections between frame theory (as developed within linear algebra) and operators (as developed within functional analysis) in the context of quantum mechanics.

Professor Jacob White leads the Computational Prototyping Group with Professor Luca Daniel. His most significant accomplishments over the past year have been in three areas: continuing development of design experiences for the technology-enabled active learning version of 8.02 Physics II, extension of his group's fast voxel-based methods (originally developed for MRI field analysis) to nanophotonic and on-chip inductance analyses, and development of hardware and software for magnetic resonance imager static field manipulation and magnet design.

Together with Professors Daniel, Elfar Adalsteinsson, and Duane Boning, Professor White's group has continued to expand the catalog of numerical techniques for and applications of their fast Fourier transform–accelerated volume integral equation method (FFT-VIEM). Using a combination of FFT-VIEM, circulant preconditioning, adiabatic absorbing, and projection-interpolation fast frequency sweeping, the group has reduced simulation times for nanophotonic structures that are notoriously difficult to simulate (e.g., coupled ring resonators) from days to minutes. In addition, the group has developed a fast implicit approach to representing coil-to-tissue maps for computing fields in human tissue for MRI applications, and they are testing strategies for including fine-scale metallic implants; both components will be part of MARIE2.0 (our increasingly popular simulation suite for analyzing fields in magnetic resonance imagers).

For the last several years, Professor White's group and colleagues have been building up expertise, infrastructure, and computational strategies for manipulating quasi-static fields to improve magnetic resonance imaging. Over the past year, they have demonstrated the benefits of static field manipulation for brain chemistry spectroscopy and selective excitation (particularly important in fetal imaging). Also in the past year, their open-source local multi-coil driver arrays and the associated computational tools for selecting coil currents have been used in more than a half-dozen research studies worldwide. In addition, they have been exploring the feasibility of hand-held MRI in a small unit, which is useful for infant and limb point-of-care diagnosis.

Professor Jeffrey Grossman and his team focus on the computational and experimental design of novel materials for applications in energy conversion, energy storage, and separations. Significant results from this year include the development of a new machine-learning algorithm that can find deeper meaning in the data from molecular dynamics simulations, commonly used by thousands of research groups and companies. The group also created a new way to make a stable, transparent electrode by coating silver nanowires with graphene. In addition, the group made a host of novel electronic devices from fossil fuel feedstocks (tar, coal, and pitch) that in some cases are competitive in performance with state-of-the-art devices while exhibiting extremely high resilience and flexibility and involving ultra-low manufacturing costs relative to traditional materials.

Professor Jae Lim's group is involved in the development of image and video processing methods. During the past year, the group reported a new method for more efficiently encoding images and video by reducing the number of bits used for transmitting information such as prediction direction in intra-frame encoding. Efficient image and video compression has a variety of applications such as video communication and streaming.

Professor Muriel Médard leads the Network Coding and Reliable Communications Group, a highly cooperative research group with collaborations that include the Computer Science and Artificial Intelligence Laboratory, the Laboratory for Information and Decision Systems, Brown University, Duke University, Northeastern University, Pennsylvania State University, Stanford University, ETH Zurich, the Technical University of Braunschweig, the Budapest University of Technology and Economics, the University of Cyprus, Trinity College Dublin, Nokia, and CodeOn. The group's central theme is networking, with a special emphasis on new practical and theoretical developments in the area of network coding. Specific achievements during the past year include the development of a noise-based decoding algorithm that is capacity achieving and promises to considerably speed up communications circuits, the use of network coding in 5G 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 Vivienne Sze and the Energy-Efficient Multimedia Systems Group focus their research on the development and implementation of energy-efficient and high-performance systems for various multimedia applications such as computer vision, machine learning, autonomous navigation, 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 (VLSI) circuit implementation. The group's work this year has been concentrated on three areas: joint architecture and algorithm design for energy-efficient real-time robot exploration, measurements of eye reaction times on a smartphone to serve as objective biomarkers supporting diagnosis and tracking of neurodegenerative disease progression, and energy-efficient depth estimation to reduce the on-time of time-of-flight (ToF) sensors. Their work on the co-design of algorithms and hardware for robot exploration (in collaboration with Sertac Karaman) makes it feasible to compute Shannon's mutual information for an entire map; this determines the next location that the robot should explore to reduce the uncertainty of an unknown environment in a manner that is orders of magnitude more energy efficient than off-the-shelf solutions. Additionally, in their work on developing a robust and low-cost platform for measuring eye reaction times (in collaboration with Thomas Heldt and Charles Sodini), they have collected and analyzed approximately 50,000 measurements from more than 30 healthy subjects across a wide range of environments. Finally, they have shown that, with lightweight algorithms, they can reduce the on-time of ToF sensors while maintaining depth map accuracy on both rigid and non-rigid objects. Reducing the on-time of ToF sensors reduces overall system power as well as interference in applications with multiple sensors (e.g., when multiple users use augmented reality).

Over the past year, Professor Gregory Wornell's research has focused on new theory and methods for fast, accurate, and interpretable machine learning; new transfer learning technologies for applications with limited training data; and new redundancy techniques for creating reliable sensor arrays from unreliable elements.

In the area of machine learning, the Wornell group continues to develop foundational theory to interpret and further develop advanced methodologies. Their recent work seeks to address key challenges in reducing the heavy computational demands of learning and the difficulties practitioners experience in interpreting the resulting processing. Among their latest results are new spectral techniques for problems related to regression and classification with high-dimensional data. In particular, they have developed a generalized Fourier analysis of Boolean functions and used it to automatically generate and efficiently select informative low-dimensional features from raw data. The resulting methods not only offer excellent prediction performance but, as a result of the Fourier structure, are efficient to implement in software or hardware and provide the kind of good interpretability that existing neural networks typically do not.

A second thrust of the group's research has been on problems in learning from limited training data, which arise in diverse applications (including a number of the computational imaging and computer vision challenges on which the group is focused in related research). In such settings, labeled training data frequently are expensive to obtain, often requiring manual labeling by humans. A general approach to reducing the amount of labeled data required for good performance is based on transfer learning, whereby small amounts of training data for the task of interest are augmented with larger amounts of available training data for one or more different but related tasks, which are adapted accordingly. In this area, the group's recent results include both a new unsupervised data-alignment methodology for adapting training data to new domains in classification tasks and a methodology for generating a good classifier network for a task directly from a suite of existing pre-trained classifier networks for related tasks. The group's approach to the latter is based on modal decomposition techniques developed in their earlier research, and the effectiveness and practicality of the approach have been demonstrated in several key image classification settings.

In the area of sensing and imaging, the group's recent results include a methodology for reliable sensing from unreliable sensor arrays. Sensor arrays are deployed in a wide range of commercial and defense applications, and many have protracted development cycles, are used in remote and harsh environments, and have long operating lifetimes.

During operation, such arrays can degrade in a variety of ways (e.g., due to physical damage or component failure), and repairing and/or recalibrating these systems can often be impractical or prohibitively expensive. As such, operators are forced to either abandon this equipment or accept the resulting performance degradations. However, the group showed that in traditional applications such as geolocation of sources in the environment, the redundancy typically present in the arrays can be exploited using signal processing to automatically detect incorrectly functioning elements and suppress the role their data play in the sensing task. The resulting methodology is computationally efficient to implement and, more importantly, provides system designers with new architectures and more flexibility in designing reliable high-performance, cost-effective sensing systems.

Professor Lizhong Zheng spent the past year working on extending his theory of universal feature selection to develop new ways of understanding and using deep learning. The theory developed by Zheng's group involves a novel geometric approach to analysis that helps reveal some complex relations in learning problems. This approach is thus particularly powerful in applying deep learning in more complex cases (e.g., domain knowledge, multi-modal data). Zheng and his group have developed software packages and have started several projects on transfer learning for image processing and use of learning algorithms in communication problems. This work is being completed in collaborations with Lincoln Laboratory and SenseTime and as part of a Multidisciplinary University Research Initiative (MURI) project.

Biomedical Science and Engineering

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

Magnetic resonance imaging in pregnancy involves a variety of unmet clinical needs as well as opportunities for scientific discovery. However, relative to imaging in pediatric patients and adults, current state-of-the-art MRI hardware and software platforms and methods deliver unreliable and inferior image quality for the mother and fetus, primarily as a result of the unpredictable motion of a noncompliant subject, the fetus. A dominant focus of Professor Elfar Adalsteinsson and the Magnetic Resonance Imaging Group is improving the image quality and robustness of fetal MRI. With support from the National Institutes of Health, they seek to develop, validate, and apply novel imaging methods in the fetus and placenta; this work is done in close collaboration with Professors White, Daniel, and Polina Golland as well as colleagues at the MGH Martinos Center for Biomedical Imaging and Boston Children's Hospital (BCH). Another active domain of research in the group and with collaborators is the design of algorithms and hardware for optimization of RF transmission and main magnetic fields that stand to offer improved image quality for fast imaging and novel applications such as body imaging and fetal MRI. This effort involves a strong collaboration with Professors Daniel and White along with colleagues at the MGH Martinos Center.

The Bioelectronics Group, led by Professor Polina Anikeeva, develops fiber-based and nanomagnetic interfaces to the electroactive organs within the body. Over the past year, the group has developed magnetic interfaces to the adrenal gland, demonstrating remote control of the stress hormones epinephrine and corticosterone. This approach is rooted in the inherent sensitivity of the adrenal cells to heat and the ability of the magnetic nanoparticles to undergo hysteretic heating in the presence of weak, rapidly alternating magnetic fields. The group has also made advances in fiber-based fabrication, demonstrating a robust approach to creating porous fiber-based scaffolds for nerve growth. This approach relies on thermal drawing of polymer-salt composites followed by leaching of the salt crystals. These porous fibers can then serve as filaments in three-dimensional printing of scaffolds with complex geometries matching those of biological nerves.

In a collaboration with the research groups of Professor Anantha Chandrakasan, Professor Yoel Fink, and Professor Cem Tasan, the Bioelectronics Group has developed programmable fiber-based artificial muscles geometrically and functionally inspired by cucumber tendrils. In this work, bimorph fibers composed of high-performance plastic and an elastomer with drastically different coefficients of thermal expansion were prestrained up to 1,000%. Following the prestrain release, the fibers assumed helical geometry, and application of a modest thermal stimulus resulted in coil tightening and linear actuation. These miniature devices, with lateral dimensions from microns to millimeters, can lift 650 times their weight and afford rapid actuation with tens of millisecond latencies. This technology could open applications in medical robotics, aerial vehicles, and prosthetic limbs.

Professor Louis D. Braida and the Sensory Communication Group investigate topics in three broad areas: hearing aids, 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 this work is to develop improved aids for people with profound sensorineural hearing and/or visual impairments. 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 (e.g., signal processing, automatic speech recognition), 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 past year, Braida and his group have continued their work on a phonemic-based tactile display for speech communication. Their tactile device consists of a 4 × 6 array of vibrators that fit around the user's forearm between the elbow and the wrist on both the dorsal and ventral surfaces. They have developed a unique haptic code for each of the 39 phonemes of the English language, and these codes can 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 vibration at different locations and directions on the tactile array. Experimental results indicated that naive participants are able to identify the 39 haptic phonemes with a high degree of accuracy (approximately 90%) following several hours of training. Based on this promising result, the group has conducted experiments on identification of words and phrases formed from the haptic symbols.

A major focus of the group's research over the past year has been increasing the rates of communication that can be achieved with the tactile device, such that they will be comparable to those achieved by deaf-blind users of natural methods of tactual communication (i.e., on the order of 60 to 80 words per minute). Currently, the effective rates of communication achieved by users of the tactile display are estimated to be in the range of 30 to 35 words per minute. With the goal of doubling these rates, the group has conducted experiments to determine optimal time intervals between phonemes and between words; in addition, they have explored remapping the haptic phonemes to take the statistical properties of English into account and examined improved methods of training users to decode the tactile signals.

Based on the performance of deaf-blind individuals who are experienced in the use of natural methods of tactual communication, it is known that communication through the skin is possible. The group's current research, however, 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 not only provides benefits to people with profound sensory deficits in terms of giving them greater access to the world around them, but also has broader applications for people with normal sensory abilities in situations where hearing and sight may be diminished.

The research in Professor Dennis Freeman's group focuses on the cochlear mechanisms that underlie the extraordinary properties of our sense of hearing, especially sensitivity to low-amplitude sounds and acute frequency selectivity, which are hallmarks of mammalian hearing. Previously the group showed that the tectorial membrane, a gelatinous structure that stimulates the sensory receptor (hair) cells in the inner ear, supports traveling waves of motion and that these traveling waves play a key role in shaping the frequency selectivity of hearing. Work during the past year has focused on understanding the hearing deficits that occur when CEACAM16, an important adhesion protein, is knocked out of the mouse genome. Previous research has shown that CEACAM16 mutants suffer from progressive hearing loss with significantly faster onset than normal wild-type mice. This result offers unique opportunities to understand basic mechanisms of the progressive hearing losses that affect about one third of adults between the ages of 64 and 75. Interestingly, CEACAM16 mutants also have an unusually large number of very-high-level spontaneous otoacoustic emissions that decrease in size and number with age. CEACAM16 is expressed primarily in the tectorial membrane. To better understand the mechanism of this mutation, Freeman and his group measured material properties of mutant tectorial membranes using nanoscale indentation. They found that the stiffness of mutant tectorial membranes is more than five times smaller than that of wild types. As with normal tectorial membranes, radial excitation of mutant tectorial membranes generates longitudinally propagating waves. However, the radial responses decay more than three times faster in mutants than in normal mice. Most puzzling is the fact that the decay of radial motion is accompanied by an increase in longitudinal motion. This type of mode conversion has been seen in other mouse mutants and in humans, but never with such large amplitudes. The group is currently analyzing models of the tectorial membrane to better understand the significance of such mode conversion. These results are expected to improve our understanding of cochlear mechanisms in general and progressive hearing loss in particular.

Professor James Fujimoto and the Biomedical Optical Imaging and Biophotonics Group perform research in biomedical optical imaging and optical coherence tomography (OCT). The group's research spans technology development, fundamental studies, and clinical applications. The group performs collaborative studies in ophthalmology with the New England Eye Center of the Tufts University School of Medicine, New York University, and Oregon Health and Sciences University; breast and prostate cancer surgical studies with the Beth Israel Deaconess Medical Center; gastroenterology/endoscopic research with the Boston VA Healthcare System; and image processing studies with the University of Erlangen–Nuremberg. They also work with industry collaborators including Thorlabs, Praevium Research, and Topcon Healthcare Systems.

During the past year, Fujimoto and his group began enrolling patients in a clinical study to reduce rates of repeat breast cancer lumpectomy surgeries using nonlinear microscopy on surgical specimens. Lumpectomy is a standard surgical treatment for breast cancer and has favorable cosmetic outcomes. However, up to 25% to 30% of patients require repeat surgeries because cancer is present on, or close to, the surgical margin. The group has developed nonlinear microscopy technologies, surgical specimen handling, and pathology/surgical workflows that enable rapid assessment of specimens by pathologists during surgery. This can provide real-time information to guide surgical decision making and avoid repeat surgeries.

The group's randomized, controlled study, which involves nearly 100 patients, is being performed in collaboration with a multidisciplinary team that includes surgeons, pathologists, and radiologists at the Beth Israel Deaconess Medical Center. Future multi-center clinical studies as well as commercialization will ultimately be necessary. However, if successful, this research could decrease rates of repeat breast cancer surgeries, reducing patient morbidity as well as health care costs. Moreover, it could provide pathologists and surgeons with a versatile new method for rapidly evaluating surgical specimens, which would improve outcomes in many types of cancer surgeries.

Fujimoto's group is continuing research in optical coherence tomography. The group and their collaborators were responsible for the invention of OCT in the early 1990s and co-founded start-up companies that facilitated commercialization by Carl Zeiss in ophthalmology and by LightLab Imaging in interventional cardiology. OCT has become a standard technique in ophthalmology, with an estimated 20 to 30 million imaging procedures worldwide every year. A recent review estimated that, between 2008 and 2015, OCT saved over $17 billion in US health care costs for treatment of age-related macular degeneration.

OCT is also an emerging modality for intravascular imaging, where it has elucidated the pathogenesis of myocardial infarction and is used to guide interventional procedures. OCT is being developed in many other clinical and fundamental research applications as well.

Fujimoto and his group are working in collaboration with the New England Eye Center, the Oregon Health and Sciences Center, and other clinical and industrial partners in continuing research on OCT in ophthalmology. The group is especially enthusiastic about a new collaboration with Philip Rosenfeld of the Bascom Palmer Eye Institute, who pioneered pharmaceutical treatment for age-related macular degeneration. The group is developing advanced OCT technologies with higher speed and resolution than the current generation of commercial instruments and performing studies to investigate the pathogenesis of and identify markers for disease progression and treatment. If successful, these methods could facilitate new treatments for blinding eye diseases and reduce pharmaceutical trial times.

Working in collaboration with the Boston VA Healthcare System, the group is continuing investigations on the use of endoscopic OCT for detecting pre-cancerous changes in the upper GI tract. The aim is to guide biopsies and assess ablative therapies (e.g., radio frequency ablation) for the treatment of dysplasia and cancer. Their newest-generation OCT technology achieves imaging speeds that are 10 to 20 times faster than commercial endoscopic OCT, enabling high-resolution volumetric imaging of large areas, which is necessary for detection of GI pathology. They have developed a suite of devices including imaging capsules that can generate micron resolution maps of subsurface esophageal structures in unsedated patients as well as miniature imaging probes for use with standard endoscopes to perform micron-scale resolution imaging in the GI tract. Studies with patients are ongoing at the Boston VA hospital.

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

- Advancing their work demonstrating that people with very early stage Parkinson's disease can be distinguished from healthy controls through analyses of subtle differences in timing while typing, Professor Gray and her group reported data in support of the possibility of monitoring therapies through remote monitoring at home. This work leveraged advanced machine learning and the pervasive availability of the Internet to overcome the limitations of the current standard of testing (in a clinic with a motor disorder specialist). The group's research opens the door to new strategies for titrating current therapies and evaluating the efficacy of new therapies.
- The MIT Catalyst Program (established in RLE through the Madrid-MIT M+Visión Consortium) continues to demonstrate an accelerated pace and volume of innovation. As of June 30, 2019, 8 of the 16 Catalyst projects had been transitioned to commercial development (through licensing to start-ups or existing ventures). After a gap in recruiting for a new cohort of Catalyst Fellows, the program was successfully re-launched with the fifth cohort of fellows, who began in January 2019. They are on track to being as successful as the prior cohorts.
- The MIT IMPACT Program provides a semester-long experience for Boston-area trainees (postdocs and advanced predocs) to help them become more strategic in developing their research and career plans with the aim of increasing the chance of impact (above and beyond publication). In response to many requests that the program be made available to people outside the Boston area, the group piloted an IMPACT-US version in which a mix of in-person and remote sessions were held. Reviews were comparable to the positive reviews received for the IMPACT-Boston implementation.

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.

The need for accurate analysis of low-abundance nucleic acids and proteins is ubiquitous in biological science and engineering. Revolutionary nucleic acid amplification techniques have enabled single-copy detection of nucleic acids but have many issues restricting their implementation in diagnostics and various applications. Protein analysis lags severely behind because there are no protein amplification techniques. Han and his group recently reported a universal technique that unprecedentedly achieves billion-fold enrichment of both nucleic acids and proteins directly in complex biological samples, which may play an enabling role in the rapid analysis of ultra-low-abundance biomolecules (especially proteins) in many fields. The group demonstrated direct detection of attomolar nucleic acid and protein biomarkers in crude clinical samples within an hour, validating the generic functionality of the technique in clinical diagnostics.

Professor Thomas Heldt directs the Integrative Neuromonitoring and Critical Care Informatics Group at the Institute for Medical Engineering and Science (IMES). Using physiologically based dynamic models, the group leverages multivariate bedside monitoring data—on the second to hour time scale—to understand the physiology of the injured brain, to improve diagnoses, and to accelerate treatment decisions for the critically ill. The group continues very strong and active collaborations with clinicians at BCH, the Boston Medical Center, MGH, and the 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 among Professor Heldt's group, Robert Tasker (BCH), and James Holsapple (Boston Medical Center) further validated a model-based, calibration-free, and noninvasive approach to continuous intracranial pressure estimation in a diverse set of patients ranging in age from 2 years to over 80 years and spanning a diverse set of etiologies, including traumatic brain injuries, hydrocephalus, stroke, cerebrovascular malformations, and metabolic disorders. The estimates are essentially as accurate and as precise as the invasive measurement, requiring drilling a hole into the patient's skull and advancing a catheter into the brain tissue or cerebrospinal fluid space. The results of this work are being published in a series of papers, with the first appearing in the *Journal of Neurosurgery: Pediatrics*.

In a comparatively nascent line of neuromonitoring research, Professor Heldt has teamed up with Professors Vivienne Sze (RLE) and Charlie Sodini (IMES, Microsystems Technology Laboratories) to use cameras on consumer-grade electronic devices (smartphones, tablet computers) as a means of measuring the features of eye movements. Such features have been shown to be affected in neurodegenerative diseases and may therefore serve as a digital biomarker of disease progression. With graduate students Gladynel Saavedra-Peña and Hsin-Yu Lai, Heldt and his colleagues were able to demonstrate that their features of interest could be recorded to clinical-grade accuracy, and they recorded and analyzed over 30,000 reactive eye movement tasks among healthy volunteers for comparison and exploratory data analysis. They are currently in discussions with clinicians from the Memory Disorders Unit at Massachusetts General Hospital to translate their approach to clinical populations with mild cognitive impairments and early-stage Alzheimer's disease.

Professor Timothy Lu's Synthetic Biology Group made several major advances this year, as detailed below.

- *Synthetic promoters with enhanced cell state specificity (SPECSs)*: Promoters are sites in the genome that, in response to transcription factor binding, regulate gene expression. Lu and his group developed synthetic promoters offering more precise control of gene expression than natural promoters. Synthetic promoters can be used to distinguish tumor cells from healthy cells, a key requirement for immunotherapy. The group introduced synthetic promoters into cells via lentiviral delivery and, through fluorescence-activated cell sorting, next-generation sequencing, and machine learning–based computational analysis, identified promoters conferring strong expression levels only in certain cell states (SPECSs). They found SPECSs that exhibited different activity in glioblastoma cells and breast cancer cells relative to healthy cell lines of the same tissue. Other SPECSs were active only at certain stages of differentiation of a liver organoid. Elucidation of gene expression networks can provide a deeper understanding of cellular processes and new therapies for cancer.

- *Computing and memory in living cells:* Ubiquitous, durable, and compatible with biological functions, DNA is an ideal data storage medium. Because the nucleotides constituting DNA are the same across all species, they provide a universal format for processing data. Lu and his group have developed stochastic and deterministic memory systems for data storage in DNA. Stochastic memory systems generate random mutations in defined DNA addresses, with each mutation containing information only about the occurrence of a single event. Deterministic memory systems generate predetermined mutations in defined DNA addresses corresponding to events that can be analyzed at the population level or at individual memory loci within single cells. The group's deterministic recording system, the DNA-based Ordered Memory and Iteration Network Operator (DOMINO), uses DNA editing to create computing circuits, converting information stored as mutated sequences into fluorescent signals. DOMINO has single-nucleotide resolution for encoding both memory and computing operations in bacterial and mammalian cells. With DOMINO, logic operations are executed based on mutations introduced into a DNA locus targeted by two input guide RNAs. The group also developed a circuit for mammalian cells in which predefined mutations are introduced as a sequential cascade over time. This information can be analyzed as both digital and analog data by calculating the percentage of mutated arrays or the percentage of each memory state. This research advances artificial learning gene circuits and monitoring of DNA computing and memory in living mammalian cells.

- *Bacteriophage*: In response to emerging antibiotic-resistant bacterial infections, Lu and his group are developing synthetic bacteriophage (phage)–based antimicrobials. Bacterial populations acquire resistance to phages, reducing the potential efficacy of phages as antimicrobial agents. Phages interact with bacterial surfaces via tail fibers, which serve as landing gear to initiate infection of the bacteria. The group identified parts of tail fiber proteins that determine which type of bacteria a given phage infects and advanced a high-throughput strategy to genetically engineer these host range–determining regions through site-directed mutagenesis. They obtained phages with altered host ranges that suppress bacterial growth and prevent the appearance of resistance in vitro and in vivo in a mouse skin infection model.

This year, the work of principal research scientist Stefanie Shattuck-Hufnagel and her research group focused on developing integrated models of the production, perception, and learning of speech. Specifically, they developed a feature-cue-based speech analysis system to serve as a model of the initial stages of human speech recognition; tested the roles of rhythm, periodicity, and motor entrainment in the organization of speech and non-speech behaviors; and investigated the alignment between co-speech gestures of the hands and spoken prosody to facilitate a comprehensive model of speech production planning that includes the sentence, its prosody, and its gestures.

The overall goal of the group's 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 the development of effective new tools for clinical intervention and improvements in current algorithms for automatic speech recognition, as well as potentially enabling the teaching of second languages in a manner that reduces or eliminates a foreign accent.

The group has expanded investigations of the cognitive process of speech production planning and speech perception to include a focus on individual acoustic cues to the distinctive features that define and contrast the phonemic categories of a language. In this way, they have supplemented ongoing 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 result suggests that both speakers and listeners represent and manipulate individual acoustic cues to contrastive categories. If this finding 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. With regard to co-speech manual gesturing, the group has 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. These findings again suggest that speakers and listeners manipulate individual cues to linguistic structure, and thus 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, the group found that toddlers age 2 to 3 years produce a complex intonational marker for phrase-level prominence, suggesting that even at this young age children are in control of much of the adult inventory of pitch accent types. This result casts doubt on the currently dominant view that small children cannot accurately control the fundamental frequency contours of their utterances. In addition, in collaborative work with Juan Godino (University of Madrid) in the domain of speech disorders, the group has shown that an individual-feature-cue-based approach to analysis of the speech produced by patients diagnosed with Parkinson's disease exhibits considerable promise for early diagnosis of this disorder, during the period of time when treatment can still be effective. This finding suggests that Parkinsonian speech is distinct from that of typical speakers in terms of not only the traditional diagnostic stop consonants but almost all 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 on 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 human speech processing.

Research in Professor Collin Stultz's Computational Biophysics Group is focused on three areas: understanding conformational changes in biomolecules that play an important role in common human diseases, using machine learning to develop models that identify patients at high risk of adverse clinical events, and developing new methods to discover optimal treatment strategies for high-risk patients. The group uses an interdisciplinary approach combining computational modeling and machine learning to accomplish these tasks.

In recent years, Stultz and his group have focused on using machine learning for patient risk stratification and clinical decision making. More generally, they have worked with their collaborators at MGH to develop a joint MIT-MGH center for cardiovascular engineering and data science in the area of personalized medicine. The proposed center represents a combined effort between computer/data scientists at MIT and the Division of Cardiology at MGH. This work has been supported by the MIT J-Clinic and the MIT-IBM Watson AI Lab.

The Computational Physiology and Clinical Inference Group, directed by Professor George Verghese, is focused on bedside informatics: using physiologically based dynamic models to interpret multivariate monitoring data collected in settings ranging from acute care to home monitoring. The group interacts closely with Professor Thomas Heldt's Integrative Neuromonitoring and Critical Care Informatics Group.

Currently, research in the group is primarily aimed at more extensive and refined use of time-based capnography, which records partial CO_2 pressure as a function of time in exhaled breath. Capnographs are ubiquitous in hospital settings and ambulance systems and function as a noninvasive and effort-independent monitoring modality. However, only a fraction of the information they provide is currently extracted and used. This work is being carried out with the close involvement of Baruch Krauss at BCH and his clinical collaborators in various hospitals, who have collected valuable original data for these studies.

After initial explorations using methods inspired by machine learning, the group has been working on developing, analyzing, and applying simple mechanistic models of the capnogram with clinically meaningful parameters that can be identified in real time during patient monitoring and used to assess the patient's status. Recent work in the group has shown how these parameters can be used to estimate normalized versions of airflow, yielding valuable information on respiratory status.

Notably, the group's research on capnography has been significantly advanced in recent years by UROP and SuperUROP students. The models involved have good circuit analogs, allowing for easy entry into the area by EECS undergraduates, and the students are motivated by the opportunity to work with real data on medically interesting and relevant problems. A journal paper in preparation has undergraduate students as lead authors.

A two-year project funded by Philips Healthcare and involving collaborators and data collection at BCH (for asthma data) and the Beth Israel Deaconess Medical Center (for data from patients with congestive heart failure and/or chronic obstructive pulmonary disease) is underway, with Professor Thomas Heldt as principal investigator. The capnographic data from these hospitals will be supplemented by other clinical data, allowing enhancement of current algorithms and a fuller evaluation of the value added by capnography.

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 Group have been working on several areas this past year, including immunology. The group has developed a system that combines microfluidics and electronics to measure immune system molecules from blood in 25 minutes with only a drop of blood. The system has no bulky optics and can be easily extended to measurement of many molecules in parallel.

Nanoscale Materials, Devices, and Systems

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

Professor Karl Berggren's research group develops nanofabrication methods for applications in quantum technologies and nanotechnologies. Areas of research focus include (1) superconducting nanotechnologies for radiation detectors, quantum circuits, and superconducting nanoelectronics; (2) nanoscale field emitters for investigation of strong-field physics and development of ultra-fast nanoelectronics and low-voltage vacuum electronic devices; and (3) investigation of fundamental interactions of electrons, ions, and photons with matter for applications in lithography, microscopy, light generation, and nanofabrication.

In the last year, Professor Berggren's group has developed a new technique for analyzing ultra-fast electron emissions driven from matter by strong optical fields. This technique has been used to conclusively demonstrate that when intense, few-cycle optical pulses of light illuminate nanometer-scale antennas, sub-optical-cycle electron packets with durations of less than one femtosecond are generated at the antenna surface. Such electron packets could be used as near-field probes for microscopy or spectroscopy with both nanometer spatial and attosecond temporal resolution. These probes could be useful for investigation of electron dynamics in molecular or solid-state systems. The analysis technique developed by the Berggren group has been shown to be highly sensitive to both the optical and electronic properties of nanoantennas. The group was able to perform in situ characterization of the temporal response of gold nanoantennas with a temporal resolution of 100 attoseconds.

Professor Dirk Englund and his team develop computing, networking, and sensing technologies using techniques from quantum information science. The past year's major research accomplishments include the development of nanometer-scale MRI reference beacons for imaging in scattering media, improved interfaces between quantum memories and photons, a new architecture for machine learning accelerators, advances in quantum computing–based optimal measurements and quantum neural networks, and the development of complementary metal-oxide-semiconductor (CMOS)–integrated quantum control of diamond spins (with MIT professor Ruonan Han). A pair of start-up companies out of Professor Englund's laboratory (LightMatter Inc. and Dust Identity Inc.) have been named among Boston's top start-ups to watch and received more than $40 million in private funding. During his upcoming sabbatical, Professor Englund will be engaged as co-founder of a new start-up, QuEra, to scale up a leading quantum computing platform coming out of the MIT-Harvard Center for Ultracold Atoms. Englund also initiated (as PI) a new MURI program titled Ab-Initio Solid-State Quantum Materials: Design, Production, and Characterization at the Atomic Scale. On the teaching side, Professor Englund introduced a new course on quantum technologies (6.S063/6.644: Principles and Applications of Quantum Optics) in fall 2018 that received strong feedback. He was awarded a Bose Research Fellowship for research on a new type of electron hydrodynamics logic device with co-investigators Nuno Loureiro and Leonid Levitov.

Professor Yoel Fink and his research group focus on extending the frontiers of fiber materials from optical transmission to encompass electronic, optoelectronic, and even acoustic properties. Two significant opportunities now present themselves. First, can we expect that fiber functions will escalate in a predictable manner, creating the context for a "Moore's law" analogue in fibers? Second, as fabrics occupy an enormous real estate, not the least being the surface of our bodies, could they offer valuable service to augment the human body? Some highlights of the group's activities this past year are detailed below.

- *Diode fibers for fabric-based optical communications:* Professor Fink's group established a unique platform to integrate the high-quality semiconductor diodes (e.g., light-emitting and photo-detecting diodes) commonly used in consumer electronics into thermally drawn polymer optical fibers, which can be woven into fabrics. Optical communication was established between fabrics containing receiver-emitter fibers. Heart-rate sensing was also realized, demonstrating all-fabric physiological-status monitoring systems. Advanced Functional Fabrics of America, a US Manufacturing Innovation Institute focusing on revolutionary fabrics and textiles, is rapidly advancing a variety of potential applications of these fibers in sensing, defense, and communications.

- *Microfluidics in structured multimaterial fibers:* A novel microfluidics method based on a fiber format was established to construct microchannels with highly tunable cross-sectional geometries and a broad range of materials. This work addressed many restrictions inherent to conventional planar microfabrication techniques that impose challenges on the design of flow fields and external forces that can be imposed onto fluids and particles. The fiber was exploited for high-throughput cell separation. This technology will open a number of opportunities to shape hydrodynamic flows and electric fields for applications in cell separation, electrowetting, and electrotaxis.

- *Distributed quantum fiber magnetometry:* A thermally drawn fiber with hundreds of embedded photodiodes connected in parallel and a hollow optical waveguide containing a fluid with nitrogen-vacancy diamonds was fabricated for distributed quantum sensing. Such a distributed water-immersible quantum fiber magnetometer promises new applications for remote detection and tracking in a range of fields including geophysics, ferrous metal detection, and biomedical sensing.

The research of Professor Jing Kong and the Nano-Materials and Electronics Group focuses on the challenge of developing the chemical vapor deposition (CVD) synthesis routes of various two-dimensional (2D) materials, characterizing their structures and properties, and assessing their applications. They are designing new strategies to make graphene, MoS_2, and other novel 2D materials with desired physical and chemical qualities. Their in-depth understanding of how to make those materials enables them to develop new architectures for high-performance electronics and energy conversion. Recently the group has focused on large-area CVD synthesis of 2D materials and development of highly porous, low-density, high-surface-area aerogel materials.

The Kong group had several interesting results over the past year. They found that by modifying the SiO_2/Si substrate via O_2 plasma while optimizing MoS_2 synthesis, monolayer MoS_2 patterns can be directly synthesized on the SiO_2/Si mask. More interestingly, this monolayer MoS_2 can be transferred by delamination from the SiO_2/Si surface using water (without a polymer protection layer). Detailed investigations were carried out to understand the mechanisms of this method, which has the potential to reduce costs related to lithography and other processing steps in future semiconductor device fabrications. The Kong group also investigated graphene transfer using paraffin, which becomes a liquid when mildly heated. They found that the interactions between paraffin and graphene are much weaker than the interactions between graphene and poly(methyl methacrylate) (PMMA), the widely used polymer support for graphene transfer. Paraffin leaves less residue on graphene and can be used to reduce graphene wrinkles by transferring using warm water. The average sheet resistance of graphene transferred by paraffin is much lower than with PMMA. This result will be very useful for devices being fabricated with CVD graphene.

Over the past year, Professor Luqiao Liu and his research group focused on investigating novel spintronic devices and materials. They had a pair of major achievements, as detailed below.

First, they exhibited strong coupling between microwave photons and nanoscale ferromagnetic magnons. Hybrid quantum systems have been extensively studied to harness advantages of distinct physical systems and realize functions that cannot be achieved with any individual sub-system alone. Recently, coupled microwave photon-magnon systems have received great attention as a potential approach to realizing strong light-matter interactions. To overcome the weak coupling strength between a single spin and the microwave field, millimeter-sized ferromagnetic metals or insulators with large spin numbers have been employed for reaching strong coupling. While great success has been demonstrated in achieving coherent sensing and control over the magnonic quantum state using this architecture, one important issue remains unresolved: whether such a system is scalable for achieving integrated hybrid quantum systems. In their recent work, the group showed that by enhancing single spin coupling strength using lithographically defined superconducting resonators, they could reach high cooperativities between a resonator mode and a Kittel mode in nanometer-thick Permalloy wires, with the number of spins for reaching strong coupling being reduced by more than three orders of magnitude relative to previous studies. Moreover, they confirmed the scaling law of coupling strength by varying magnetic volumes and extracting single spin coupling strengths. This highly engineerable device design and the large coupling strength with nanomagnets provide a direct avenue toward hybrid quantum systems that can benefit from various magnon physics.

Second, the group systematically studied the antiferromagnetic dynamics in two-dimensional antiferromagnet $CrCl_3$. Antiferromagnetic spintronics is an emerging field with the potential to realize high-speed logic and memory devices. Antiferromagnetic dynamics are less well understood than ferromagnetic materials, partly due to their high intrinsic frequencies that require specialized terahertz (THz) techniques to probe. Recently, the group carried out broadband microwave absorption spectroscopy of the layered antiferromagnet insulator $CrCl_3$ and observed a rich structure of resonances arising from quasi-two-dimensional antiferromagnetic dynamics. Due to the weak interlayer magnetic coupling in this material, they were able to observe both optical and acoustic branches of antiferromagnetic resonance in the GHz frequency range and a symmetry-protected crossing between them. By breaking rotational symmetry, they further showed that strong magnon-magnon coupling with large tunable gaps can be induced between the two resonant modes. All of these effects were captured with analytical solutions to the Landau-Lifshitz-Gilbert equation, and the extracted values of exchange field and saturation magnetization were consistent with magnetometry measurements. The group's results show that $CrCl_3$ can be a versatile platform for studying antiferromagnetic dynamics with conventional microwave electronics.

Professor Farnaz Niroui and her newly formed research group focus on pushing the limits of nanoscale processing to develop platforms for active devices and systems by studying and utilizing the physical phenomena that uniquely arise at nanometer dimensions. This leads to emerging applications in electromechanical systems, optoelectronics, and quantum technologies. To engineer such systems, the group also focuses on developing methodologies that enable fabrication, dynamic tuning, and metrology with nanometer precision, resolution, and control. This is implemented through an interdisciplinary approach integrating device physics, engineering, and materials science. Their recent research efforts include the development of an approach to control and tune surface adhesive forces such that mechanically reconfigurable structures with sub-10-nm precision are achieved. In another project, they have demonstrated a programmable self-assembly technique through which chemically synthesized nanoscale building blocks are deterministically formed into functional units with tailored structures and properties.

Over the past year, Professor Yang Shao-Horn and his group elucidated a universal reaction mechanism responsible for electrolyte oxidation on high-energy positive electrodes and shortening of Li-ion battery life. Their recent work in electrocatalysis of water splitting, especially oxygen evolution reaction, showed that increasing metal-oxygen covalency or lowering the Fermi level into the oxygen p band makes not only metal but also oxygen an active site for catalyzing oxygen evolution. Extending this concept to the study of reactivity between highly covalent Ni-based oxide electrodes and carbonate-based electrolyte reveals that carbonate dissociative adsorption on surface oxygen sites of Ni-based oxides increases significantly with increasing metal-oxygen covalency. Such dehydrogenation generates protic species, which can react and degrade electrolyte salt, and dehydrogenated organic species, which increase impedance of ion-coupled electron transfer at the electrode/electrolyte interface. This proposed mechanism is supported by ex situ Fourier transform infrared (FT-IR), Raman, and nuclear magnetic resonance measurements and more recently in situ FT-IR measurements, which provide unprecedented information on the parasitic species formed upon electrolyte oxidation as a function of voltage.

Photonic Materials, Devices, and Systems

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

Professor Marc Baldo was the director of the DoE-sponsored Center for Excitonics, an Energy Frontier Research Center whose principal mission is to supersede traditional electronics with devices that use excitons to mediate the flow of energy. Whereas the former rely on expensive and energy-intensive fabrication processes, the latter are far more suitable for the large-scale production that would be needed to generate sufficient solar cells to have a significant impact on the world energy supply. Professor Baldo’s own research program currently centers on solar cells, light-emitting devices, and spintronic switches. A key research accomplishment of the past year was his group’s demonstration of coupling between silicon solar cells and singlet exciton fission in the molecular semiconductor tetracene. Originally proposed by David Dexter in the 1970s, this coupling promises to increase the maximum efficiency of silicon solar cells to over 30%. The fission process is used to effectively double the photocurrent obtained from the blue and green portions of the visible spectrum. The coupling was achieved using thin layers of hafnium oxynitride. The mechanism involved is presently unknown and will be the subject of future work.

A second result was the stabilization of organic light-emitting molecules through tuning of the excited state lifetime. This work is relevant to organic light-emitting devices (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. In their research, the 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 seven-fold change in exciton lifetime. The dominant role of exciton lifetime suggests that the performance of the best OLED materials can be further improved by engineering the device structure for rapid extraction of the energy stored in excitons.

Professor Vladimir Bulović and his group study the physical properties of nanostructured thin films, interfaces, and devices. Their fundamental findings are applied to development of optoelectronic, electronic, and photonic devices that in the past included lasers, photodetectors, solar cells, transistors, memory cells, chemical sensors, and micro-electro machines. In particular, over the last year the group's research focused on the development of high-efficiency perovskite photovoltaics (PVs) and lightweight flexible solar technologies. In this work, supported by the Eni-MIT Solar Frontiers Center and the MIT-Tata GridEdge program (which Bulović co-directs and directs, respectively), the MIT-made perovskite PVs demonstrated a new power conversion efficiency record of more than 25%. Bulović and the group are developing methods for scaling up the production of solar technologies and have installed a slot-dye coater and a blade coater in the MIT.nano upper cleanroom. To date, these tools have demonstrated 16% efficient rapidly coated PVs, which are the first active devices fabricated in MIT.nano. In addition, in work on the vapor-phase deposition technique for scalable fabrication of PVs, the group has described a new coating method for perovskite thin films. This advancement led to the recent launch of Swift Solar Inc., a start-up company directed by Bulović's former postdocs. Earlier start-ups formed by Bulović's students and emerging from the group's work are also doing well. For example, Kateeva Inc. employs over 400 people and produces technology that has reached more than 100 million consumers, and Ubiquitous Energy Inc. has raised over $20 million to advance new transparent solar cells. Also, six new US patents based on the group's work have been issued over the last year, spanning light-emitting devices and micro-electro-machine technologies.

Professor Peter Hagelstein's group has continued theoretical and experimental studies related to condensed matter nuclear science, including cold fusion and a variety of related anomalies. For example, seeking evidence of phonon-mediated nuclear excitation transfer, the group has carried out experiments with radioactive Co-57 on steel plates subject to stimulation by applied stress and temperature. They have produced many positive results on the lower energy 14.4 keV transition in Fe-57 consistent with an induced delocalization of excitation. Also, they have found evidence of induced angular anisotropy on the higher energy lines at 122 and 136 keV.

Basic models of phonon-induced nuclear excitation transfer do not predict the effects observed, since destructive interference strongly hinders the indirect coupling associated with excitation transfer. Models augmented with asymmetric loss result in a dramatic increase in indirect coupling; however, the indirect coupling predicted by these augmented models falls short by orders of magnitude from what is observed in experiments. Last fall the group proposed that, if sufficiently large, off-resonant shifts in the intermediate states could be effective in removing destructive interference effects. A model of the off-resonant energy shift of the deuteron was developed this spring, and the resulting shift in binding energy is large. Models of phonon-mediated nuclear excitation transfer augmented with this effect appear to predict indirect coupling commensurate with what is observed in experiments.

The Hagelstein group's experimental results are significant in that the phonon-nuclear coupling they have been studying for many years appears to be accessible experimentally, opening up a new field of basic research. The group's theoretical results are significant in that they provide a foundation for understanding excess heat in the Fleischmann-Pons experiment and understanding the many anomalies seen in other experiments.

Eventually, the group hopes to develop an engineering discipline in connection with these effects, in support of the ongoing development of an associated commercial technology.

Professor Qing Hu studies terahertz quantum cascade lasers and electronics and sensing and real-time THz imaging using quantum cascade lasers and focal-plane cameras. His group has achieved many world records in terms of the performance of their THz quantum cascade lasers, including but not limited to the highest operating temperatures in the pulsed mode and the continuous wave mode. They have performed real-time THz imaging at a video rate of approximately 20 frames per second. In addition, they have developed a novel tuning mechanism that is qualitatively different from all other tunable lasers and have achieved continuous tuning over a broad frequency range. More recently, they have developed the first THz laser frequency combs and demonstrated dual-comb spectroscopy. Their experiments have the potential to lead to improvements in sensing, imaging, and high-bandwidth communications.

Professors John Joannopoulos and Marin Soljacic work together as a team in the area of nanophotonics. They are excited about their group's recent breakthrough discovery in the field of light emission by moving electrons. The radiation produced when free charges interact with media has played a key role in modern physics. Among the innumerable applications are free-electron lasers, lithography, electron microscopy, spectroscopy, and recent biomedical diagnosis and therapy technologies based on Cherenkov radiation. Nevertheless, one question in particular has remained unanswered for decades: how much energy can ultimately be extracted from a free charged particle? The group answered this question by theoretically deriving and experimentally validating a fundamental limit on the spontaneous photon emission and energy loss from free electrons. Moreover, their "upper-limit" theory applies universally, from the simplest homogenous media to the most complex metamaterials and metasurfaces.

Theoretically, the group had two surprising results. First, their theory shows that slow (nonrelativistic) electrons are capable of generating stronger radiation than fast (relativistic) electrons when they travel at a subwavelength separation from designed nanophotonic structures. This finding is a new discovery against common physical intuition; it is typically believed that faster electrons provide stronger radiation. This result may provide an alternative path for compact and efficient radiation sources using nonrelativistic electrons rather than giant accelerators. Second, the group discovered that free-electron radiation can be enhanced by many orders of magnitude by coupling free electrons with photonic bound states in the continuum. Such strong enhancement is also captured by the divergence of the upper limit for lossless dielectric media. These two theoretical findings may serve as the foundation for a next generation of free-electron lasers that operate with low-energy electrons and significantly reduced lasing thresholds.

Experimentally, the group obtained supporting evidence from two independent quantitative measurements (one in the visible regime and one in the infrared regime) of Smith-Purcell radiation (free-electron radiation generated from periodic structures). The line shapes of the measured spectra followed the predictions of the group's upper-limit theory. This work provides a unified framework that describes the general interaction between electrons and photonic environments and may lead to further theoretical and experimental breakthroughs in related fields such as high-energy and accelerator physics, photonics and plasmonics, and spectroscopy in chemistry. From a technological point of view, the work reveals a plethora of enticing possibilities for future applications. Examples include efficient slow-electron radiation sources, ultra-low-threshold free-electron lasers, accurate biomedical diagnosis and therapy, and high-resolution electron energy loss spectroscopes.

Professor Steven Johnson leads the Nanostructures and Computation Group. His research focuses on two areas: the influence of complex geometries, particularly at the nanoscale, on solutions to partial differential equations, especially for wave phenomena and electromagnetism, and high-performance computation including fast Fourier transforms, solvers for numerical electromagnetism, and large-scale optimization.

In a sequence of publications over the past year, his group established important advances in the theory and design of optical "metasurfaces," thin large-area structures with nanoscale patterns that mimic the effects of much larger devices such as curved lenses. Although directly modeling such huge devices is computationally intractable, the Johnson group combined large-scale optimization with techniques to stitch together the results of many smaller simulations in order to computationally search a huge space of potential metasurfaces to find the optimal design for challenging problems such as achromatic lenses. Indeed, the computer can be allowed to choose every nanoscale "pixel" of the surface using the group's method, a process known as "topology optimization" that can lead to the discovery of completely unexpected designs. Such techniques offer the possibility of a new generation of compact lenses, sensors, holography, polarizers, and other optical devices.

Johnson and his group also showed how techniques similar to those used in designing metasurfaces and solar cells can be applied to a completely different kind of wave problem: energy extraction from ocean waves by buoy platforms. In a collaboration with the group of MIT professor Dick Yue, they applied mathematical ideas from optimizing solar cells to show that collections of buoys along a coastline can exhibit enhanced absorption relative to isolated buoys but that there are surprising new upper bounds to the attainable enhancement over broad frequency/angular ranges closely resembling known limits of solar cells. These upper limits both provide a design benchmark and identify the key parameters for maximum performance of future ocean-energy systems.

Professor Rajeev Ram and the Physical Optics and Electronics Group pursue investigations in two major thrusts: integrated photonics and electron transport in semiconductors. The group's current work focuses on unconventional CMOS computing, microsystems for the measurement and control of cellular metabolism, and thermodynamic limits of photonics.

Professor Michael Watts and his Photonic Microsystems Group focus on 3D integration of silicon photonics with CMOS electronics and on-chip lasers for a variety of applications, including ultra-low-power wavelength division multiplexed (WDM) optical communications, optical phased arrays, optical beam steering, low-phase-noise optical-microwave oscillators, and microwave signal generation. Professor Watts's group has demonstrated the largest optical phased array ever produced, at 4,096 elements, projecting the MIT logo in the far field. Building on this demonstration, Professor Watts has applied these results to chip-based LIDAR (light detection and ranging) technologies, achieving the largest scan angle of any chip-based optical phased array at 51 degrees. Professor Watts and his group also demonstrated a new record in low-power silicon modulators, achieving less than 1 fJ per bit in modulators running at 25 Gb per second in the world's first 300-mm silicon photonics platform. Additionally, combining ultra-low-power silicon modulators with 3D wafer CMOS integration, the group demonstrated the world's lowest power communication link at just 250 fJ per bit, a result that is sure to impact low-power communication links in future high-performance data centers.

Principal research scientist Kyung-Han Hong and the Optics and Quantum Electronics Group are leading the development of novel ultra-fast mid-infrared (mid-IR) lasers for applications in laser filamentation, electron acceleration, and surface treatment of space optics. Hong joined Lincoln Laboratory in July 2018 and has been working on multiple projects related to laser development and nonlinear optics at Lincoln as well as RLE. He and his group made progress in a number of areas over the past year, as detailed below.

- *High-power femtosecond mid-IR Cr:ZnSe (chromium doped zinc selenide) lasers:* The group acquired a state-of-the-art high-power femtosecond mid-IR laser based on a Cr:ZnSe amplifier (IPG Photonics). The laser generates 220-fs, 1.2-mJ, 2.4-mm pulses at a repetition rate of 1 kHz with excellent shot-to-shot energy stability. It has been used for studying mid-IR laser filamentation and developing a mid-IR optical parametric amplifier (OPA) for application in relativistic electron acceleration under the DoE Accelerator Stewardship Program.

- *Experimental verification of resonant radiation in mid-IR laser filamentation:* The resonant radiation in a laser filament resembles the dispersive wave or Cherenkov radiation in optical fibers and plays an important role in soliton dynamics. The group experimentally verified, for the first time, the resonant radiation of mid-IR laser filaments with multi-octave-spanning supercontinuum generation (SCG) using the 2.4-μm, 220-fs Cr:ZnSe laser. High-energy, stable, robust laser filaments were generated, and on-axis resonant radiation at 1.1- to 1.4-μm wavelengths was clearly observed and confirmed by a plasma-assisted phase matching analysis and numerical simulations (in collaboration with Bonggu Shim's group at Binghamton University).

- *Mid-IR optical parametric amplifiers:* Using the Cr:ZnSe laser as a pump, the group developed a highly efficient OPA with a zinc germanium phosphide crystal. The amplified spectrum simultaneously covers the mid-IR range of 3 to 6 mm with a high conversion efficiency of approximately 10%. This is one of the first mid-IR OPAs directly pumped by a femtosecond mid-IR laser, which offers an efficient and compact platform for a high-power mid-IR source.

- *High-repetition-rate femtosecond high-power fiber amplifiers:* The group developed a 1 MHz, 1-μJ, 2.1-μm OPA for application to strong-field electron control in nanostructures and bulk solids. A home-built multi-stage, high-power ytterbium-doped fiber CPA with a 1 MHz repetition rate was used as the pump. A chirped-pulse difference-frequency generation front end provided 2.1-mm OPA signal pulses.

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. In the past year, a focus of their research has been on improving the control and coherence of noisy intermediate-scale quantum devices. With collaborators from the Singapore University of Technology and Design, they have devised a novel control technique that allows unprecedented spatial resolution (at the nanoscale) by exploiting a quantum controller (a single spin in diamond) to drive the evolution of other nuclear spin qubits. Also, with collaborators from Yale University and the California Institute of Technology, they have discovered new quantum error correction (QEC) codes that do not require noise-free ancillary qubits to achieve noise-protected quantum sensing. They have further extended these ideas to find QEC codes that provide exponential savings in the number of qubits required to protect quantum information against the noise of a common random fluctuator. This promises to bring the strength of QEC to near-term devices, where it was thought not to be achievable. In addition, with collaborators from Argentina, the group has studied limits to the control of complex quantum systems as a means of assessing whether decoherence and relaxation pose fundamental limits to the control of quantum devices of increasing size. In particular, the group (in collaboration with Professor Seth Lloyd at MIT and colleagues from Dartmouth and Duke) has found that by exploiting Hamiltonian engineering techniques, it is possible to reach the prethermal regime, 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 Cappellaro and her group also continued their work on quantum sensing. Among this year's efforts, they addressed the problem of measuring static fields by exploiting additional ancillary qubits in the system. This strategy is broadly posed to significantly improve the performance of quantum sensors by exploiting even small amounts of quantum entanglement. The group first demonstrated how a nuclear spin qubit associated with the nitrogen vacancy center can be used to up-convert a DC signal and detect transverse magnetic fields to which the sensor is typically insensitive. This enables the use of a single nanoscale sensor to implement vector magnetometry, a task that thus far has required an ensemble of sensors, which sacrifices spatial resolution. In addition, inspired by optimal control techniques that have shown broad success in quantum computation, Professor Cappellaro and collaborators from LENS (European Laboratory for Non-linear Spectroscopy) in Italy developed a novel approach to designing optimal control for quantum sensing. While in quantum computation the goal is perfect fidelity of the operation, sensing is typically a compromise between canceling noise effects and retaining the interaction with the external signal to be measured. A novel metric for optimization based on sensitivity is thus needed. This enables obtaining optimal dynamic decoupling sequences experimentally demonstrated to improve sensing.

Professor Isaac Chuang's group studies theoretical and experimental quantum information science and seeks to harness the laws of physics to solve difficult problems faster than is possible with conventional computers. In 2018, the Chuang group and collaborators at Lincoln Laboratory published results demonstrating control of single-ion quantum bits above a CMOS chip using integrated digital-to-analog converter voltage sources. Together with Google, the group also co-developed a novel methodology for identifying and predicting the location of phase transitions during the training of neural networks employing an information bottleneck for balancing memorization and generalization. In addition, in a joint effort with IBM and Lincoln Laboratory, the group published a method for engineering the Hamiltonian of nitrogen-vacancy center qubit systems to improve sensing and control.

Professor Kevin O'Brien's newly formed research group, Quantum Coherent Electronics, focuses on developing quantum devices critical to the realization of superconducting quantum computers such as nonlinear traveling wave circulators, isolators, and amplifiers. Professor O'Brien delivered an invited talk at the 20th anniversary of the development of the superconducting qubit in Tsukuba, Japan.

Professor William D. Oliver, research scientist Simon Gustavsson, and Professor Terry Orlando direct the Engineering Quantum Systems Group, a multi-university, multidisciplinary research team that focuses 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 Lincoln Laboratory. The focus over the past year was on projects related to the use of novel materials and improvements to the fidelity of single and coupled superconducting qubits.

In a project performed in collaboration with Lincoln Laboratory and Professor Pablo Jarillo-Herrero, the group developed a superconducting qubit comprising a graphene junction. Graphene is a type of two-dimensional material that can be engineered to exhibit the behavior of a Josephson junction, one of the building blocks of a superconducting qubit. In this work, for the first time, the group demonstrated temporal coherence of a circuit comprising graphene, in this case a superconducting qubit exhibiting Rabi oscillations and Ramsey interferometry. The advantage of such graphene qubits is that the qubit frequency is tunable using an applied voltage rather than an applied current as is standard in conventional superconducting qubits.

In a second project performed in collaboration with Lincoln Laboratory, the group produced state-of-the-art single-qubit and two-qubit fidelities in a three-qubit system. Using these devices, fabricated at Lincoln Laboratory, the group demonstrated single-qubit fidelities exceeding 99.9% and two-qubit fidelities exceeding 99.5%. Both fidelities are beyond the most lenient thresholds for quantum error correction protocols. The group is currently using these gates to demonstrate prototype quantum algorithms in a series of studies performed in collaboration with Professor Seth Lloyd. As a next step, they will incorporate 3D integration technology to expand the number of qubits, reduce cross talk, and improve overall performance.

In the Engineering Quantum Systems Group and elsewhere around the world, there have been tremendous improvements in coherence times and the achievable gate fidelities of superconducting qubits. As quantum information science moves from a laboratory curiosity to the threshold of technical reality, with multiple corporations investing in and supporting these technologies, there is an opportunity for major growth in a new discipline: quantum engineering. This year Professor Oliver, in collaboration with Professor Marc Baldo and Eric Dauler, launched the Lincoln-RLE Center for Quantum Engineering and its companion industrial component, the Quantum Science and Engineering Consortium.

In addition, Professor Oliver has partnered with MIT's Office of Digital Learning to create several online professional development courses via MIT xPRO that target different areas of quantum computing and quantum communication (Introduction to Quantum Computing; Quantum Algorithms for Cybersecurity, Chemistry, and Optimization; Practical Realities of Quantum Computation and Quantum Communication). Now in their second year, these courses have attracted more than 1,600 learners worldwide.

Professor Jeffrey H. Shapiro and Franco N.C. Wong primarily work on theory and experiments related to reaching ultimate quantum limits in communication, imaging, and precision measurements at optical frequencies, where quantum noise is often dominant and conventional techniques are known not to reach ultimate performance limits. This year the group has had several significant achievements. For example, they continued to develop the floodlight quantum key distribution (FL-QKD) protocol, their novel method for securely distributing encryption keys. In particular, their theoretical work showed that quadrature phase-shift keying (QPSK) could nearly double FL-QKD's secret-key rate (SKR) relative to the SKR achievable with binary phase-shift keying (BPSK). Last year, the group conducted a table-top BPSK FL-QKD experiment that realized a 1.3 gigabit per second SKR for channel attenuation, equivalent to a 50-km-long optical fiber connection. They are now upgrading their FL-QKD setup from BPSK to QPSK operation. In other theoretical work, they established a framework for proving FL-QKD's security against a coherent attack. Coherent attacks are the most powerful in the QKD attack hierarchy (composed, in order of increasing power, of individual attacks, collective attacks, and coherent attacks). FL-QKD's proven security is currently against collective attacks. To reach coherent-attack security, the group must show how channel monitoring can measure permutation-invariant constraints on light retained and received. Work on that task is underway.

The group also achieved significant experimental results in generating photons in a single well-defined spatiotemporal mode, which is essential for measurement-based photonic quantum computing owing to that architecture's reliance on interference between independent single photons. By customizing the spontaneous parametric down-conversion process and controlling the spectral profile of the pump laser, the group generated single photons with 99.2% purity. Their technique will be useful in quantum photonic applications, such as scalable quantum networks, that require multiple quantum interference measurements.

In a non-quantum area—non-line-of-sight (NLoS) imaging—the group has made important advances in terms of the theory of phasor-field (P-field) imaging. NLoS imaging, colloquially known as imaging around corners, would be a boon to many application areas, including autonomous vehicles. The group's NLoS imaging research addresses active imaging, in which around-the-corner information is obtained by (1) laser illuminating a diffusely reflecting wall that is visible to the sensor and that reflects light into the hidden space and (2) measuring light returned to the sensor from hidden-space reflections after another reflection from the visible wall. The P-field is a theoretical construct that allows concepts from conventional LoS imaging to be applied advantageously to NLoS imaging. Previous theory related to P-field imaging has not addressed how it is affected by specular reflections or occlusions in the hidden space, nor has it characterized the impact of laser speckle on P-field imaging or the signal-to-noise ratio of the P-field image. The group's recent publication in *Optics Express* has provided a set of primitives that properly account for specular reflections and occlusions, and work is currently underway on speckle effects and signal-to-noise ratios.

Personnel

RLE headquarters had one promotion this year, with Stephanie Muto being promoted to fiscal officer. Todd Numan (environment, health, and safety [EHS] officer) left RLE to become EHS officer for the central MIT Environment, Health, and Safety Office. Following Todd's departure, Marie Gentile was hired in April 2019 to become RLE's new EHS officer.

Faculty Honors and Awards

Professor Luca Daniel was awarded the 2019 Thornton Family Faculty Research and Innovation Fellowship and was nominated for the 2019 MIT Teaching with Digital Technology Award.

Professor James Fujimoto received the Hyung-Woo Kwak Memorial Award from the Asian Pacific Retinal Imaging Society.

Professor Thomas Heldt was named a distinguished lecturer by the IEEE Engineering in Medicine and Biology Society and a visiting professor by ETH Zurich. Also, he won the EECS Burgess ('52) & Elizabeth Jamieson Award for Excellence in Teaching.

Research scientist Phillip Donald Keathley received the 2018 Young Investigator Award from the Air Force Office of Scientific Research (AFOSR).

Professor Luqiao Liu received an AFOSR Young Investigator Award in October 2018.

Professor David Perreault received a Second Prize Paper Award from the IEEE Power Electronics Society (for "Multitrack Power Conversion Architecture"). Also, he won the Best Paper Award at the 2019 IEEE Workshop on Control and Modeling for Power Electronics (for "Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators").

Professor Yang Shao-Horn was awarded the Mok Hing Yiu Distinguished Visiting Professorship at the Hong Kong University (2019–2025).

Professor Vivienne Sze received four awards in 2018–2019: the 2019 Edgerton Faculty Award, the 2018 Google Faculty Research Award, the 2018 Facebook Faculty Award, and (with Amr Suleiman) the 2018 Symposium on VLSI Circuits Best Student Paper Award (for "Navion: A Fully Integrated Energy-Efficient Visual-Inertial Odometry Accelerator for Autonomous Navigation of Nano Drones").

Professor Jacob White received the 2019 Bose Award for Excellence in Teaching.

Professor Gregory Wornell won the 2019 IEEE Leon K. Kirchmayer Graduate Teaching Award.

Professor Martin Zwierlein was awarded the 2019 Class of Vannevar Bush Faculty Fellowship in May 2019.

Staff Awards

The following RLE community members won 2019 Infinite Mile Awards from the Office of the Vice President for Research: Rachel Drake, manager of human resources at RLE headquarters; Samantha Farrell, administrative assistant for Professor Vladimir Bulović; and Stephanie Muto, fiscal officer at RLE headquarters.

Student Awards

Stefan Raufer, a speech and hearing bioscience and technology student working at Massachusetts Eye and Ear, was awarded the 2019 Peake Research Prize. Raufer, supervised by Professor Heidi Nakajima, was recognized for his work showing that the anatomy and motion of the human cochlear partition differ in crucial ways from the generalized classic view of mammalian cochlear mechanics and his efforts related to understanding low-frequency sound transmission of the human ear.

The 2018–2019 Claude E. Shannon Research Assistantships were awarded to two outstanding RLE graduate students. Ganesh Ajjaganadde, an EECS doctoral student supervised by Professor Gregory Wornell, was recognized for his significant accomplishments in coding theory and its applications. EECS doctoral student Anny Xijia Zheng, supervised by Professor Vincent Chan, was recognized for her significant accomplishments in cognitive optical networking.

Power Electronics Research Group (PERG) member Yiou He received a 2019 Applied Power Electronics Conference (APEC) Outstanding Presentation Award for her paper "Series Diode Balancing and Diode Evaluation for High-Voltage High-Frequency Power Converters."

PhD student Junru Li from Professor Wolfgang Ketterle's group received the 2019 Chinese Government Award for Outstanding Self-Financed Student Abroad.

John Simonaitis, a graduate student in Professor Karl Berggren's group, received a 2019 NSF Graduate Research Fellowship.

Emily Toomey, also a graduate student in Professor Berggren's group, was awarded a Mass Media Fellowship by the American Association for the Advancement of Science and a Graduate Study Fellowship by the IEEE Council on Superconductivity. In addition, she was selected for the EECS 2019 Rising Stars Program.

PERG member Haoquan (Tony) Zhang received the Best Student Presentation Award in the Power Electronics and Grid Integration category at the 2019 IEEE Photovoltaic Specialists Conference (for his paper "A Power Management Approach for Laterally-Arrayed Multi-Bandgap Concentrated Photovoltaic Systems").

Affirmative Action and Outreach Activities

Over the past year, RLE's Muriel Médard has successfully led the effort to create the IEEE Millie Dresselhaus Medal, in honor of the former RLE principal investigator.

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

Marc Baldo
Director
Professor of Electrical Engineering and Computer Science