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 in 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 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 many 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 $43.240 million in fiscal year 2020, 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 2020, 296 graduate students and 93 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 (DoD) agencies, the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Department of Energy. 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 2019–2020 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. The Ketterle group's major result during the past year was the realization of spin models using ultra-cold atoms in optical lattices.

Simple models of interacting spins capture the properties of many magnetic materials and extend to other systems including bosons and fermions in a lattice, systems with gauge fields, high-T_c superconductors, and systems with exotic particles such as anyons and Majorana fermions. So far, spin transport has been studied only in the isotropic Heisenberg model. Professor Ketterle and his group implemented the Heisenberg XXZ model with adjustable anisotropy and used this system to study spin transport after quantum quenches from imprinted spin helix patterns.

Using lithium-7 and Feshbach resonances, the group was able to realize the Heisenberg model with widely tunable interaction parameters and study spin physics over the entire range of anisotropies $\Delta = J_z/J_{x,y}$. For $\Delta = 1$, they retrieved the isotropic Heisenberg model. For $\Delta = 0$, they realized the so-called XX model, which is a special starting point for investigations since it is exactly solvable in one dimension by mapping the spins to non-interacting fermions.

An important question is how relaxation time depends on the spatial period of the spin pattern. A quadratic dependence implies diffusive transport, whereas a linear dependence characterizes ballistic transport. For anisotropy $\Delta = 0$, the group observed ballistic transport. When anisotropy was increased, a crossover to diffusive transport occurred. For positive anisotropies, the dynamics ranged from anomalous super-diffusion to sub-diffusion depending on anisotropy, whereas for negative anisotropies there was a crossover in the time domain from ballistic to diffusive transport. This behavior contrasts with expectations for the linear response regime and raises new questions with respect to understanding quantum many-body dynamics far from equilibrium.

The research of Professor Vladan Vuletic focuses on quantum information processing, quantum computing, and other quantum technologies such as novel sensors. A particular focus is on how to use quantum correlations (entanglement) that are stronger than classical correlations to improve atomic clocks and atomic interferometers, to enable quantum computation, and to control photons individually. Recent highlights for the Vuletic group include the demonstration of the largest quantum "Schroedinger cat" states to date with 20 particles (the Schroedinger cat can be dead and alive at the same time), the first demonstration of repulsive interactions between two individual photons, and first results on the search for dark matter of unknown origin in our universe using precision quantum measurements.

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. A highlight was the observation of universal sound diffusion in a strongly interacting Fermi gas. Transport of strongly interacting fermions governs modern materials but also nuclear fission, the merging of neutron stars, and the expansion of the early universe. The group observed a universal quantum limit of diffusivity in a homogeneous, strongly interacting Fermi gas of atoms by studying sound propagation and its attenuation via coupled transport of momentum and heat. In the superfluid regime, sound diffusivity attains a universal value set by the ratio of Planck's constant and the particle mass. This finding of quantum-limited sound diffusivity informs theories of fermion transport and has relevance for hydrodynamic flow of electrons, neutrons, and quarks. This research was accepted for publication in *Science*.

In their work on a novel experimental apparatus, the group was able to cleanly realize a Bose-Einstein condensate at the lowest Landau level—a bosonic analogue to the quantum Hall regime of electrons in high magnetic fields—by using a novel technique, geometric squeezing, that exploits the non-commutativity of space upon rotation. They observed the Heisenberg limited width of the wave function, given by the atoms' zero-point cyclotron motion.

In their molecule laboratory, the group was able to induce strong, resonant dipolar interactions between molecules using microwave dressing, a novel method that opens up the pathway toward strongly interacting dipolar quantum gases. They explained the resonant behavior with a simple two-level model whereby microwave dressing enables molecules to attract each other with the full value of the transition dipole moment.

The group's Fermi gas microscope gave them the first images of the full density of a Fermi-Hubbard gas with single-atom and single-lattice site resolution. The Fermi-Hubbard model is believed to hold the key to our understanding of high-temperature superconductivity. The new technique allowed direct observation of doublon-hole correlations and a novel thermometry method based on the fluctuation-dissipation theorem.

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.

Professor Yufeng (Kevin) Chen's research focuses on investigating millimeter-scaled biomechanics, distilling the underlying physics, and applying these principles to developing novel robots at the insect scale. His group is working on developing millimeter-scale muscle-like actuators and incorporating them into agile and robust robotic systems.

During the past year, Chen and his group demonstrated controlled flight in an insect-scale flapping-wing robot. This initial result was published in *Nature*. Also, for the first time, they demonstrated soft actuators that exhibit sufficient power density and controllability to enable hovering flight. In contrast to state-of-the-art existing microscale aerial robots, their robot can sense and survive in-flight collisions. These properties make the robot suitable for navigation tasks in cluttered environments. Currently they are working to solve challenges such as incorporating battery and circuitry into insect-scale vehicles, fabricating a swarm of these systems, and demonstrating collective behaviors. In the long term, they envision their robots being used in applications such as search and rescue and assisted agriculture.

In addition, the group has developed a quadrupedal robot that can climb on inverted and inclined surfaces via capillary adhesion and lubrication forces. Their 1.4-g legged robot can achieve inverted climbing and turning at a speed of 0.3 cm per second. This initial result was published in *Robotics and Automation Letters*. Their work proposes a novel adhesion method for sensing and actuation-limited microscale systems that has the potential to enable future microrobots to inspect complex environments such as the inside of an engine. Their goal is to extend their design to the development of new mechanisms for microrobotic manipulation.

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's team has 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 power transformers. The modeling includes losses due to skin and proximity effects and has been validated for frequencies to 300 kHz. Tests are planned for new designs up to the 40 kW level with high power transfer efficiencies (above 95%).

The magnetic induction communications work has been performed in collaboration with the MIT Sea Grant College Program. The initial work has been expanded theoretically to enable broadband magnetic sensors and magnetic induction transmission for undersea communications as a means of conveying data from underwater sensors to an autonomous surface vehicle. 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 being constructed and will be subjected to a long-duration test for reliability.

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 continue to be 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 used to study the possible cleaning of face masks exposed to viruses.

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 represents an example of how basic electromagnetic principles can be applied to yield improved practical devices with global applications.

Professor James Kirtley (now post-tenure) of LEES is a specialist in electric machinery and electric power systems. Professor Kirtley and several other RLE investigators are collaborating with Professor Zoltan Spakovsky of the Department of Aeronautics and Astronautics to develop a large, high-speed permanent magnet motor/generator system for aircraft propulsion applications.

William Lynch is continuing experiments on lithium ion cells to understand their dynamic performance. This year, Lynch and graduate student Mostafa Negm have developed and are improving balancing mechanisms for these cells.

Professor Jeffrey Lang's research focuses on electromagnetic and electromechanical energy-conversion, motion-control, and sensing systems. Its applications involve 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.

Cochlear implants driven by external microphones have become the standard method of care for profound sensorineural hearing loss. In collaboration with Massachusetts Eye and Ear and Columbia University, Lang and his group are developing implantable microphones as assistive hearing devices. Fully implantable systems with implantable microphones provide uninterrupted access, including during sleep; easier handling for the young and elderly; more comfort during physical activities; benefits from acoustic enhancements; and cosmetic benefits. The group developed and experimentally validated electromechanical models that can guide the design of two different microphones, one for implantation in the middle ear and the other for implantation in the cochlea alongside the electrodes that stimulate the cochlear nerves. They also carried out and experimentally verified a noise analysis of the microphones and their attendant electronics, which led to low-noise designs of the combined electromechanical and electronic systems.

Measurement of instantaneous voltage and current across and through the power distribution wiring of electrical and electronic systems can be a valuable sensing capability. For example, it permits confirmation of proper system electrification and operation and investigation of power flow, power quality, and power distortion. Examining the details of voltages and currents can also enable valuable load health monitoring and failure prevention. Of course, voltage and current measurements are usually readily available as contact measurements. However, in many cases, contactless measurements would be preferred. Lang's team developed and demonstrated a contactless measurement system for voltages and currents that can operate at the residential and industrial scales. The novelty of the system is in its immunity to external disturbances such as those injected by nearby power lines, self-induced charges and eddy currents in nearby conductors, and electromagnetic fields induced in nearby magnetizable materials.

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. They 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. For example:

- The group was awarded a $1.2 million grant for test equipment for the new T.J. Rodgers RLE Laboratory, which will be used for electronics prototyping, and the EECS core teaching laboratories.
- Graduate student and US Coast Guard (USCG) officer Tom Kane, along with other team members, received a commendation from USCG for applying the group's combat power monitoring (CPM) system onboard a Coast Guard medium endurance cutter. The system revealed motor-related faults and prevented an engine fire. This work led to a new Office of Naval Research project to develop CPM for further shipboard use with USCG and the US Navy.
- The group received a prize paper award at IEEE (Institute of Electrical and Electronics Engineers) AutoTestCon 2019 for the work that led to the installation of their CPM system on the USCG cutter.
- The team developed new techniques for spectral correlation vibration monitoring. These techniques were applied to actively identify impending faults in prototype systems for ExxonMobil and are currently being applied on board USCG and US Navy ships in the field.

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 new power conversion technologies to attain miniaturization and integration of power electronics and their use for applications in renewable energy, transportation, and industrial equipment.

This year, with Professor Lang, Perreault and his group succeeded in using piezoelectric devices for miniaturized power electronics. Most power electronic converters employ magnetic components to provide the required intermediate energy storage. However, mechanical energy storage provided by piezoelectric devices can also be used for power conversion. Piezoelectric devices have promise for achieving both high power density and high efficiency, and they offer significantly improved scaling properties relative to magnetics. The team investigated the possible energy conversion cycles that can be used for piezoelectric-resonator-based power conversion, identified the modes that are most effective in terms of their efficiency, and demonstrated high-performance converters realizing this approach. This work led to two published conference papers and a published journal paper.

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. Also, the group designed a new type of hysteresis linear motor for reticle transport in a vacuum.
- The group is designing new non-contact handling solutions for moving semiconductor elements in a vacuum with high cleanliness.
- 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.
- In another collaboration with Professor Griffith, the group is designing mechatronic solutions for new types of microphysiological systems for investigating human organ tissue growth and interactions with the microbiome and immune systems, with a focus on creating an in vitro platform for studying endometriosis lesions growing in uterine tissue. The group has designed new types of platform mechatronic flow configurations and new electromagnetic actuators for highly power-efficient microfluidic pumping.
- The group is working with an industrial partner to design new types of magnetically levitated impellers for blood oxygenation pumping. These novel pumps now experimentally demonstrate levitation and control of pumping rotation. They were successfully used for bench-level pumping of blood with acceptable results, which enabled testing on animal subjects. With funding from an NIH Small Business Technology Transfer Phase II award, the group will work toward creating a functional product targeted for use with pediatric patients.
- In a collaboration with Lincoln Laboratory, the group is designing a new type of momentum wheel for microsatellite attitude control. This design 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.

The research of Professor Vincent W.S. Chan's group focuses on cognitive network management and control. Many modern applications produce and consume data at unprecedented rates with strict reliability and latency requirements. Not surprisingly, the unpredictable nature of their traffic can induce highly dynamic network environments that threaten their viability. Unencumbered operation of these applications requires rapid actions (and reactions) by the network management and control (NMC) system, which itself depends on timely collection of network state information. Over the past year, significant results were published on this topic.

In recent work, the group has sought to identify the shortest path between a pair of nodes in highly dynamic networks. A centralized routing protocol in which an NMC system monitors the network state (e.g., link/queuing delays) is applied to determine which paths should connect different origin-destination pairs. The monitoring process can be interpreted as a sampling/decision/action process involving three steps: updating (the nodes in the network report their state to the NMC system), decision (the NMC system identifies the shortest path between each origin-destination pair and computes the subsequent report time), and dissemination (the NMC system disseminates the updated routing information and the next report time to all of the nodes in the network).

The main contributions of the group's latest work can be summarized as follows:

- Their significant sampling solution has the advantage that it makes no assumption about the underlying traffic model but learns to sample the network in such a way as to achieve optimal performance. They demonstrated the optimality of their solution through experimental findings confirming that the learned policy matches the analytical results derived.
- They designed a multi-step look-ahead policy that considers the long-term impact of a decision and minimizes the cost rate over an infinite time horizon. Experimental results showed that their new policy outperforms the old policy by 39% in terms of average cost rate.
- Given the model-free nature of reinforced learning, they demonstrated that their solution is robust to various network conditions.

The group's cognitive approach to optimally fast optical network sensing and reconfiguration has shown significant gain with respect to utilization of network resources and thus has beneficial cost impacts. The algorithm used in this work to sense and determine optical network state changes has been proven to be the optimal algorithm based on observable traffic. The algorithm also predicts and minimizes transient queues built up in the network using peak queue delays as the performance metric. During summer 2019, this body of work was tested in the network hardware of the IBM supercomputer Summit and found to have excellent agreement with measured data. The results are under review by IBM for public release.

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.

Convolutional neural networks (CNNs) have become the standard for performing complex tasks such as image classification due to their high accuracy. However, they typically require substantial computation (approximately 10^9 operations) to process a single image and a large amount of memory (approximately 10 to 100 MB) to store the fixed weight parameters and intermediate output activations. This makes it challenging to process CNNs locally on edge devices with low power and low latency. To address this issue, the team needs custom hardware accelerators to exploit the parallelism present in the computations. Due to the memory constraints on edge devices, the group focuses on networks compressed by techniques such as deep compression and trained ternary quantization, which quantize the weights to a small number of unique values (usually 16 or fewer).

Team members Alex Ji, Wanyeong Jung, Jongchan Woo, and Khushal Sethi have proposed a scalable architecture for efficiently processing compressed networks by reordering multiplications and additions. Instead of performing each multiply-and-add separately, they accumulate all of the activations multiplied by the same weight first and perform the multiplication at the end. With a small number of unique weights, the number of multiplications is greatly reduced, and consequently average energy per operation is lowered. To enable the trade-off between accuracy and efficiency, they added reconfigurability for different weight and activation bit widths. This allowed them to use shorter bit widths in applications where energy must be minimized and an accuracy drop can be tolerated. With support for residual connections and depth-wise convolutions, their accelerator can run modern networks such as ResNet and MobileNet, enabling CNN processing for a wide range of applications on energy-constrained devices including cell phones and IoT nodes.

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 robustness quantification and optimization. Applications of the group's computing techniques include biomedical measuring and imaging, silicon photonics, power delivery, and deep neural networks.

As artificial intelligence (AI) systems automate more tasks, alerting the public to possible failures is critical, especially in safety-critical (e.g., self-driving cars) and fairness-critical (e.g., hiring, lending) applications. To this end, the group developed and published methods and codes generating robustness certificates. For instance, their CNN-Cert is 366 times faster than state-of-the-art verification methods for similar certificate quality. The group's method was adopted by IBM for its Adversarial Robustness 360 Toolbox.

With the deployment of renewable sources and electric vehicle charging stations on power distribution networks, load uncertainty and scaling must be included in predictive computational tools. Daniel's group has developed and published techniques that accomplish this task via generalized polynomial chaos and stochastic testing methods. Testing on European benchmark load-profile variations (e.g., residential loads, electrical vehicle charging) showed that their tools were 100 times faster than the state of the art. They further quantified sensitivities, providing guidance for optimal allocation and planning.

The research focus of Professor Alan Oppenheim and the Digital Signal Processing Group includes exploration of new algorithms for signal processing and related applications. Their recent focus has been on binary hypothesis testing of the discrimination between multiple quantum states in the context of quantum mechanics. The discrimination problem is fundamentally different from quantum tomography, which is directed at state estimation rather than state discrimination. In contrast to the classical discrimination problem, the no-cloning theorem in quantum mechanics requires that discrimination be done on ensembles of particles prepared in the same quantum state prior to measurement. The measurement formalism considered is the use of positive operator-valued measures (POVMs); these measures have their classical counterpart in frame theory, which is well established in the signal processing community. POVM design for optimal discrimination is one aspect of the group's research objectives. A second aspect involves consideration of the operating characteristics associated with the discrimination. A particularly intriguing direction for this work is exploiting over-completeness of the measurement process. This is in analogy with the use of oversampling and noise shaping as done in classical signal processing. However, exploiting over-completeness in quantum mechanics is a relatively new and rich direction.

Professor Jacob White leads the Computational Prototyping Group with Luca Daniel and collaborates extensively with Professor Elfar Adalsteinsson's group on magnetic resonance imaging (MRI). Prior to the pandemic, he and his group were having a banner year of "in vivo" validation for their computational tools. A new algorithmic strategy in MARIE2.0, their voxel-based fast field solver, reduced the time to compute human-head-wide 3D fields from minutes to seconds, a result that was put to immediate use in a study of real-time (patient-in-scanner) safety assessment. In addition, the group's maturing suite of hardware/software tools for time-varying main field manipulation was applied to improving 2-hydroxyglutarate magnetic resonance spectroscopy of glioma patients and to designing and driving non-eye-occluding shim coils for improving pre-frontal cortex images in human visual stimulation studies.

The pandemic put a spotlight on the low-key efforts of White's students and colleagues to democratize technology using inventive combinations of computation and very-low-cost commodity hardware.

In education, the "Hands-On for Half Price" effort quietly created very-low-cost kits of sophisticated and pedagogically effective design experiences for physics and engineering undergraduates, with variants being used in 16.06 Principles: Automatic Control (Aeronautics and Astronautics), 6.302 Feedback System Design (EECS), and 8.02 Electricity and Magnetism. Remote-use versions of these kits are being developed, both for MIT and for use internationally. In collaboration with fellow Alex Shvonski, 200 mostly first-year 8.02 students will receive kits this fall to allow them to investigate conductivity (resistor piano), magnetic forces (brushless motor), power generation (brushless generator), and resonance (wireless power transfer). Also, in collaboration with EECS professor Tayo Akinwande, 50 kits are being prepared for use in control classes at Bayero University in Nigeria, although the timeline for their use is uncertain.

In research, the extremely challenging "Hand-Held MR Imager" project is attempting to put one of the safest and most diagnostically revealing technologies ever developed into every clinician's hands and into every student's classroom. This past year, White's group recorded their first spin echoes from a figure-sized prototype. The prototype uses a computationally designed spoke-and-hub magnet, one that is easily and inexpensively assembled from 64 magnets eight inches thick, one half inch wide, and one inch long. The imager's signaling system uses computationally synthesized edge dithering to generate radio frequency (RF) pulses (using Bloch-equation-based optimization) so that the signals can be created via commodity integrated circuits such as standard ultrasound pulsers and generic microcontrollers.

Professor Jeffrey Grossman and his group focus on the computational and experimental design of novel materials for applications in energy conversion, energy storage, clean water, and industrial separations. Significant results from this year include the development of a modeling framework that combines molecular dynamics with machine learning techniques to accelerate the design of novel polymer materials. Also, based on technology developed in the lab, the group spun out a (second) membrane start-up to create ultra-resilient, nanoporous, low-cost membranes with target applications in wastewater treatment. Furthermore, the group has continued its work on making "dirty carbon" too valuable to burn; over the past year, they demonstrated that metal power can be 3D printed in air, which is highly challenging otherwise, when tar is used as a binder material.

Professor Jae Lim's group is involved in the development of image and video processing methods. Previously, 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. During the past year, they continued their research on the new method. 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 Broad Institute, the Computer Science and Artificial Intelligence Laboratory, Ben Gurion University, Battelle, Brown University, the Budapest University of Technology and Economics, Maynooth University, Northeastern University, Ohio State University, the Rensselaer Polytechnic institute (RPI), Stanford University, Université Catholique de Louvain, the University of Coimbra, and the Weizmann Institute. The group's central theme is networking, with a special emphasis on low delay and reliable communications and developing the intersection of coding, networking, signal processing, and machine learning. The group continued its work on the development of a noise-based decoding algorithm that is capacity achieving and promises to considerably speed up communications circuits (in collaboration with Boston University and Maynooth University), the use of network coding in fifth-generation (5G) wireless systems requiring very low delays (in collaboration with several partners though MIT-Portugal), the development of transport protocols (in collaboration with Université Catholique de Louvain), the design of waveforms for intercept wireless communications (in collaboration with Ohio State University and Battelle), and the use of coding for in-network computation (in collaboration with RPI).

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. This year the group had major achievements in the area of efficient deep neural networks (DNNs), including designing an efficient DNN model for processing-in-memory accelerators and creating an architecture-level framework for the rapid evaluation and exploration of DNN hardware accelerators. Also, they authored a book on efficient processing of DNNs.

The group's modeling work highlights that recent DNNs designed for digital accelerators do not perform well on processing-in-memory accelerators. This suggests the need to rethink the design of DNN models (specifically regarding processing in memory) for improved accuracy and efficiency.

The group's second area of work addressed the importance of estimating energy consumption in designing domain-specific accelerators. In collaboration with Professor Joel Emer, they developed a framework called Accelergy that performs energy estimations without requiring a complete hardware description of the design, allowing for fast exploration of the accelerator design space. They showed that the framework achieves approximately 95% accuracy on Eyeriss, a well-known DNN accelerator design, and can correctly capture the energy breakdown of the components at different granularities. They held several tutorials at top-tier computer architecture conferences to help disseminate the work into the research community.

Finally, the group's book *Efficient Processing of Deep Neural Networks* provides a structured treatment of the key principles and techniques enabling efficient processing of DNNs. It includes a background on DNN processing, a description and taxonomy of hardware architectural approaches for designing DNN accelerators, key metrics for evaluating and comparing different designs, and features of DNN processing that are amenable to hardware/algorithm co-design. It was developed in conjunction with the course 6.812/6.825 Hardware Architecture for Deep Learning and will also be used in several courses outside of MIT.

Over the past year, Professor Gregory Wornell's research has focused on communication under privacy constraints, computational imaging of hidden moving scenes from scattered light, and machine learning under privacy and fairness constraints.

In the area of communication, Wornell and his group formulated and analyzed a model to address the problem of communication with a privacy constraint ensuring that the probability a sender can be geo-located is arbitrarily small. Such a constraint is important in a wealth of settings, including defense applications. The group analyzed the fundamental limits of this constraint using simple but insightful models wherein they abstracted the problem into one of obfuscating channel state information. For a variety of different such scenarios, they determined the associated channel capacities and characterized when communication at a positive rate is possible and when it is not.

In computational imaging, they developed a methodology for reconstructing "movies" of hidden scenes from the patterns of scattered light in complex environments. Activity in one portion of a room can be recovered from measurements of the spatiotemporal light patterns from naturally occurring complex objects and surfaces in a different part of the room. The methodology, which they refer to as “computational mirrors,” is based on a factorization of the scene tensor from the unknown light transport matrix obtained by imposing a prior on each in the form of a neural network. The resulting method is blind, requiring no training data and no prior information about the scene or environment in which light is propagating. Such non-line-of-sight imaging systems have a variety of potential applications.

In machine learning, the group continued to develop a foundational theory to interpret and further progress advanced methodologies. Their recent work addresses key challenges associated with ensuring privacy and/or fairness in training classifiers from data with sensitive attributes. In the privacy setting, they developed a learning methodology that performs the classification task as accurately as possible subject to an arbitrarily stringent constraint on how much information about the sensitive attribute is leaked by the output of the classifier, as measured by mutual information. In the fairness setting, their classifiers are optimized subject to a conditional mutual information constraint, referred to as “separation,” that controls for biases in the associated decision making.

Professor Lizhong Zheng’s work focuses on the theoretic aspect of machine learning. In recent years, his group developed a geometric approach to study information processing in high-dimensional learning problems. This approach is a significant step to enrich analysis tools in information theory by differentiating information pieces according to their contents and qualities and to quantify the overlap between different pieces with a geometric structure. It has become clear that such a method is particularly useful in complex information-processing problems, for example multiple tasks, multi-modal data, and dynamic statistics. Professor Zheng and his group therefore have focused their research effort on using their new tools to understand and develop solutions for a few such “more complex” problems. Particularly in some well-developed engineering disciplines such as communications, dynamic controls, economics, and networks, the current research challenges involve problems in which conventional simplifying model-based analysis methods become too inaccurate, and direct application of the current machine learning methods is often far too inefficient, due to an inability to utilize the rich structural knowledge developed in these fields. Professor Zheng’s group is making progress in developing systematic approaches, based on their geometric analyses, that combine the power of machine learning with structural knowledge to make computational methods more applicable to a wide range of engineering problems.

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.

The diagnostic utility of fetal MRI is fundamentally limited by protocols that can “freeze-frame” natural fetal and maternal motion on a sub-second time scale only for a single imaging section at a time. For a complete view of the fetal body or targeted fetal organs, a set of multiple such freeze-frame acquisitions is gathered over a span of several minutes, which routinely incurs detrimental motion-induced image artifacts that compromise clinical evaluations. Retrospective mitigation of such image artifacts relies on redundant acquisitions to infer a coherent MRI volume consistent with the observed imaging data. Alternative and prospective means of intelligent data gathering to detect and mitigate fetal motion, at scan time and with minimal human intervention, remain a driving research objective for Elfar Adalsteinsson and the Magnetic Resonance Imaging Group in collaboration with Professors White, Daniel, and Polina Golland as well as colleagues at Boston Children’s Hospital (BCH) and Massachusetts General Hospital.

Also, the group aims to transform the current workflow of fetal MRI wherein a trained technician is required to detect and react to fetal motion under latency constraints of minutes. Rather, they propose machine-driven and intelligent scanning protocols with sub-second latency for fetal or maternal motion detection and on-the-fly adaptive image acquisition that follows fetal movement in real time. Thus, they target motion-mitigated imaging that maximizes the diagnostic utility of the mother’s time spent in the scanner.

Several aspects of this “self-driving” fetal MRI are under active research. On-the-fly image quality assessment serves to classify the acquired data as either diagnostically valuable or in need of re-acquisition due to unacceptable image artifacts. The group proposed and demonstrated a trained CNN to perform such assessments with a latency of 20 ms. They quantified its performance and found that the network focused on the brain and artifact features relevant to making its classification. Initial implementations on clinical MRI scanners at BCH applied in studies of pregnant subjects demonstrated that such fast image quality assessment can indeed detect diagnostically unacceptable images and drive real-time decision making for re-acquisition in fetal imaging.

The Bioelectronics Group, led by Professor Polina Anikeeva, develops fiber-based and nanomagnetic interfaces to the electroactive organs within the body. Last year they demonstrated several mechanistically different approaches to interrogate cellular signaling. For instance, drawing inspiration from biocatalysis of nitrite into nitric oxide by iron-sulfur binding enzymes, they developed an electrocatalytic approach for nitric oxide generation in situ and in vivo. Nitric oxide is a key messenger in neurodevelopment and synaptic plasticity, processes critical for learning and memory formation. The study of this important messenger has, however, been impeded by the challenges of delivery of gaseous molecules into the body. In collaboration with Professor Karthish Manthiram in Chemical Engineering and Professor Yoel Fink at RLE, the group integrated iron-sulfide nanocatalysts into multi-material fibers to create flexible microscale electrocatalytic cells suitable for implantation into the brain. They then showed that electrocatalytic generation of nitric oxide from benign soluble metabolite sodium nitrite was sufficient to trigger receptors in the vicinity of the device, leading to local and circuit-wide neural excitation.

The group has continued to expand on modalities of wireless neuromodulation by developing a new class of magnetic nanomaterials: magnetite nanodiscs capable of transducing mechanical stimuli to neuronal membranes upon exposure to weak, slow-varying magnetic fields. Magnetic nanodiscs were engineered to support a vortex magnetization state wherein all spins are circularly aligned to collectively yield net-zero magnetization in the absence of a magnetic field. This endows them with superior colloidal stability even at diameters of approximately 100 to 300 nm and thicknesses of approximately 30 to 40 nm. Upon exposure to a weak (less than 25 mT) magnetic field, the nanodiscs assume in-plane magnetization and act as magnetomechanical levers on neuronal membranes. The group demonstrated magnetomechanical neuromodulation by targeting nanodiscs to sensory neurons from the dorsal root ganglia that endogenously express an array of mechanosensitive ion channels.

Professor Louis D. Braida and the Sensory Communication Group investigate topics in three broad areas: hearing aids, tactile communication of speech, and multi-sensory interactions.

Their long-term goal is to develop improved communication devices for people with profound sensorineural hearing and/or visual impairments. Tactile communication systems can serve as a sensory substitute for providing information about acoustic stimuli in the environment, including speech and other types of environmental sounds. They have two different approaches to tactile devices. One concerns the development and evaluation of a new generation of tactile aids with the capacity for achieving speech communication through the sense of touch alone. The second is the development of tactile aids to serve as supplements to information available through lip reading.

They continued research on a phonemic-based tactile display as a stand-alone system for speech communication. The device consists of a 4 × 6 array of vibrators that fit around the user's forearm between the elbow and the wrist on the dorsal and ventral surfaces. A unique haptic code was developed for each of the 39 phonemes of the English language, which can be concatenated to form words and sentences. The group conducted experiments to determine the optimal time interval for the spacing of phonemes in forming words, as well as the interval between words in forming phrases and sentences. In addition, they completed experiments in which participants were trained initially on reception of the haptic phonemes, followed by training on recognition of words from a 500-word vocabulary. Their research showed promising results in that learning proceeded at a pace of roughly one word per minute at roughly 80% accuracy, far surpassing the performance of the previous generation of tactile aids.

The group also began work to further develop tactile aids as supplements to lip reading. Patterns of consonant and vowel confusions that occur through lip reading alone were analyzed in experiments conducted with a profoundly deaf adult. The group then designed a method of processing the acoustic speech signal to identify properties of speech segments that are useful in reducing confusion among the segments. These properties will be encoded for display through a tactile device. For example, voiced and voiceless consonants are highly confused through lip reading. Thus, the group will implement voicing detection in their signal-processing scheme and encode the voiced/voiceless distinction through different vibratory patterns on the tactile device.

Based on the performance of deaf-blind individuals using natural methods of tactual communication, it is known that communication through the skin is possible. The group's current research has expanded the horizons of tactual communication through the development of an artificial display in which speech stimuli can be learned and perceived through the tactile sense. This research provides benefits to those with profound sensory deficits and involves 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. By virtue of resonance, traveling wave properties, and its position overlying the sensory receptors, the tectorial membrane (TM) is believed to play a significant role in determining these extraordinary properties, and recent genetic studies have confirmed the importance of the TM for cochlear mechanisms. Changes in genes that encode TM proteins, including TECTA, TECTB, OTOA, COL11A2, COL9A1, and CEACAM16, cause moderate to severe hearing deficits, even when the TM is nearly unchanged in its physical orientation and structural attachment to the sensory receptors. In particular, the CEACAM16 glycoprotein co-localizes with alpha-tectorin and beta-tectorin, and a mis-sense mutation in CEACAM16 leads to morphological changes and age-related threshold shifts in cochlear sensitivity. To study effects of age-related degradations of the TM, the group used a wave chamber to characterize the traveling wave and material properties of both wild-type and CEACAM16 mutant TMs at audio frequencies. They observed striking shifts in TM wave decay and speeds (corresponding to shifts in cochlear sensitivity and tuning) with age. Both wave speed and the spread of excitation of TM radial motions of mutant TMs are significantly reduced at the age of 9 to 15 weeks relative to 6-week-old mutants and to wild types, which have similar TM wave properties. The TM wave results in young and aged CEACAM16 mutants suggest that the CEACAM16 glycoprotein is critical for energy propagation through the matrix structure of the TM, that this energy propagation is needed for cochlear tuning and amplification, and that changes in energy propagation occur gradually with age.

The group has also made significant progress in understanding TM mechanisms. The TM is mechanically coupled to the mechanosensory receptors and is hypothesized to play a key role in determining the remarkable sensitivity and frequency selectivity of the mammalian cochlea. Despite the prominent role of the TM in cochlear mechanics and recent experimental studies that have helped elucidate the role of TM resonance and traveling waves, the dynamic material properties and mechanistic role of the TM remain unclear in cochlear models. To better understand the implications of their wave measurements for cochlear mechanics, the group worked with collaborators to develop a least-square algorithm and apply the algorithm to characterize the anisotropic material properties of wild-type and TECTB TMs at audio frequencies. They found that the TM is a highly viscoelastic and anisotropic structure with significantly higher stiffness in the direction of the collagen fibers. Although no decrease in the stiffness in the fiber direction was observed, the stiffness of the TM in shear and in the transverse direction was found to be significantly reduced in TECTB mice. As a result, the TMs of the mutant mice tended to be significantly more anisotropic within the frequency range examined. The effects of the TECTB mutation on the TM's anisotropic material properties may be responsible for the changes in cochlear tuning and sensitivity that have been previously reported for these mice. This work was published in the *Biophysical Journal*.

Professor James Fujimoto leads the Biomedical Optical Imaging and Biophotonics Group. The group's research is multidisciplinary and spans technology development, fundamental studies of disease, and clinical applications for improved diagnosis, monitoring of disease progression, and response to therapy. They have collaborative research programs in ophthalmology with the New England Eye Center, the Tufts University School of Medicine, and the Oregon Health and Sciences University; breast and prostate cancer surgery with the Beth Israel Deaconess Medical Center (BIDMC); gastroenterology/endoscopic cancer detection with the Boston VA Healthcare System; and computational imaging with the University of Erlangen–Nuremberg. They also collaborate with Thorlabs, Praevium Research, and Topcon Healthcare Systems.

Although lumpectomy is a standard treatment for breast cancer, up to 25% to 30% of patients require repeat surgeries because cancer is present on, or near, the surgical margin. The group has developed nonlinear microscopy technologies and pathology/surgical work flows that enable pathologists to rapidly assess specimens during surgery and guide surgical decision making. After a multi-year development effort, they began a clinical trial (Real-Time Assessment of Breast Cancer Lumpectomy Specimen Margins with Nonlinear Microscopy) aiming to reduce rates of repeat surgeries in breast cancer lumpectomy. This randomized, controlled study with 98 breast cancer patients is being performed in collaboration with a multidisciplinary team of surgeons, pathologists, and radiologists at BIDMC. To date, the team has imaged 28 patients (13 from the study group and 15 from the control group). Cancer was detected on or near the surgical margin in seven study group patients, and additional surgical resection was done in six patients, resulting in five patients having negative surgical margins (potentially avoiding repeat surgery). These excellent study results strongly suggest that nonlinear microscopy can reduce rates of second surgeries in breast cancer lumpectomy.

Fujimoto and his group are continuing research on optical coherence tomography in ophthalmology, working with the New England Eye Center, the Oregon Health and Sciences Center, and other collaborators. They recently renewed their NIH Novel Optical Diagnostics with Optical Coherence Tomography program, in which they are investigating age-related macular degeneration, a leading cause of blindness; in this research, they are developing improved imaging methods for diagnosis and treatment monitoring to enhance patient care and accelerate pharmaceutical development.

Professor Martha Gray leads the Biomedical Technology Innovation Group. Her research program focuses on formalizing approaches that drive innovation to create impact, particularly in the context of pre-doctoral and postdoctoral research training.

The key highlight during 2020 relates to the MIT Catalyst Program (established in RLE through the Madrid-MIT M+Visión Consortium). Catalyst continues to demonstrate an accelerated pace and volume of innovation. After a several-year gap in recruiting for a new cohort of Catalyst Fellows, the program has been successfully re-launched (thanks to a new partnership with the Department of Veterans Affairs) and is back on track with annual recruiting. The program's sixth cohort (the second in partnership with the Department of Veterans Affairs) began in January 2020. Their research phase is just beginning.

Professor Jongyoon Han leads the Micro/Nanofluidic BioMEMS Group. Their research focuses on molecular and cell separation and sorting technologies as well as various novel microfluidic and bioMEMs systems.

Most patients with COVID-19 infection recover with minor or no apparent symptoms and illnesses. Still, a small subset of patients develop very severe pneumonia, ending up in the intensive care unit with no therapeutic options other than supportive care. Although this is believed to be caused by overactive immune systems, the underlying mechanism and ways to alleviate such illness have yet to be discovered. In a collaboration with Professor Joel Voldman's group and critical care physicians at Brigham and Women's Hospital, the Han group developed a system that can quickly isolate a sufficient number of patients' immune cells from 50 µl of blood. They used the system to assess leukocyte phenotype and function in serial samples from 18 hospitalized patients with sepsis and 10 healthy subjects. Repeated sampling of sepsis patients over seven days showed that leukocyte activation (measured via isodielectric separation) and leukocyte phenotype and function were significantly more predictive of clinical course than complete-blood-count parameters. This work shows promise for rapidly and accurately detecting patients at higher risk of developing sepsis and managing those septic patients more efficiently through recovery by monitoring immune activation states in real time.

Professor Thomas Heldt directs the Integrative Neuromonitoring and Critical Care Informatics Group in RLE and 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 BIDMC in the areas of neurocritical and neonatal critical care as well as other areas of patient monitoring.

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 (ICP) estimation in an animal model of intracranial hypertension. The preliminary results suggest that the performance metrics previously reported with human subjects in neurocritical care hold up across a much wider range of measured ICP. The estimates remain 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.

In work with Vivienne Sze and Professor Charlie Sodini (IMES, Microsystems Technology Laboratories) using cameras on consumer-grade electronic devices (smartphones, tablet computers) to measure features of eye movements, the group teamed up with researchers from the Air Force-MIT Artificial Intelligence Accelerator and Lincoln Laboratory to use physiological biomarkers to understand and accelerate the training of Air Force pilots.

Professor Heldt's group continues to roll out data recording at BCH and BIDMC to collect capnographic information from emergency room patients with exacerbations of asthma and shortness of breath (for a variety of reasons). These clinical studies are currently on hold, given the COVID-19 pandemic, but the group hopes that these research restrictions will end. The goals of the data collection are to validate a noninvasive and effort-independent approach to gauge the severity of an asthma attack and to differentiate between cardiac and pulmonary causes of shortness of breath.

Professor Timothy Lu's Synthetic Biology Group uses synthetic biology to address the dysregulated cellular functioning underlying disease. Their platforms can be employed to redesign bacterial and mammalian cells as living machines, redirecting genetic programs to modulate cellular phenotypes and indicating new diagnostic and therapeutic strategies. They are seeking ways to overcome antibiotic-resistant bacterial infections by identifying drug targets for intracellular pathogens, generating antimicrobial peptides, and engineering bacteriophage. They are also advancing their biosensors to understand and eventually remodel the interactions between the human body and the microbiome. Additionally, they are exploring the intersection of synthetic biology and materials science to create engineered living materials.

High-throughput functional CRISPR-based genomic screens can elucidate highly complex host-pathogen interactions to reveal new drug targets for bacterial infections. Using CRISPR knockout and CRISPR interference screens, Lu and his group identified potential targets for host-directed therapies (HDTs) for tuberculosis (TB) by tracking genetic perturbations that improved the survival of human phagocytic cells infected with *Mycobacterium bovis* (as a proxy for *Mycobacterium tuberculosis*, the causative agent of TB). They identified genetic perturbations that improved the survival of infected human phagocytic cells and found over 100 genes that constrained the intracellular survival of *M. tuberculosis*; these genes were associated with diverse biological pathways. They then matched small molecule inhibitors to the genes, considering them as potential HDT targets.

The group is using machine learning and artificial intelligence to derive synthetic antimicrobial peptides from natural peptides. In addition, they have identified host-range-determining regions in a phage tail fiber protein. Genetically engineering these regions has yielded engineered phages with altered host ranges that suppress bacterial growth in vitro and in an in vivo murine model.

The group reviewed current models of microbiome-host interactions, including broad-spectrum interventions (fecal microbiota transplantation, antibiotics, probiotics, and prebiotics) and more highly targeted ways to understand the interactions between the human host and the microbiome, which increasingly appears to play an important role in health and disease. Also, the group is developing bacterial cell-based biosensors (i.e., genetically engineered living cells that detect specific molecules in the body or the environment) to continuously monitor the gastrointestinal tract for biomarkers of inflammatory, immunologic, and metabolic disorders.

Undesirable crosstalk among components of synthetic signaling and gene networks may impede network functioning. The group introduced crosstalk-compensating gene circuits by engineering a panel of circuits that sensed reactive oxygen species in

Escherichia coli and compensated for crosstalk via network-level signal integration; these circuits can be used for accurate interpretation of environmental signals.

The group also engineered cells to synthesize nanomaterials: a genetic circuit in the cells encodes a nanomaterial precursor-sensing module (sensor) that detects metal ions and is coupled with a material synthesis module to produce a nanomaterial-nucleating extracellular matrix. In addition, they developed a cellular adhesive made of bacterial biofilm; this functional cellular glue contains an engineered amyloid protein functionalized with a mussel foot protein and an engineered hydrophobin-like protein. They demonstrated tunable adhesion via inducible enzymatic modification with the resulting glue.

This year principal investigator Stefanie Shattuck-Hufnagel and the Speech Communication Group focused on three research projects related to modeling different aspects of human speech processing: the development of a model of feature-cue-based processing in perception, an investigation of the effects of prosodic structure (intonation and timing), and modeling of speech production planning including both prosody and co-speech gesture.

In studies of feature-cue-based processing, the group published a description of the analysis framework as well as a detailed description of the acoustic cues to flapping of /t/ that demonstrates the usefulness of the framework by identifying sociolinguistic factors reflected in different cue choices. Tools developed to increase the efficiency of acoustic analyses of feature cues included an algorithm for aligning predicted cues with the cues realized in a particular utterance. This work has led to analyses of the speech of atypical speakers as well, including speakers with Parkinson's disease and children with a variety of clinical diagnoses such as dyslexia, autism, and specific language impairment.

The group's research on the prosodic characteristics of intonation and timing has led to investigations of the role of spectral peaks in the processing of F0 contours through fricative consonants, development of a new phonetically based annotation system for spoken prosody called PoLaR, and studies of the unexpectedly early emergence of a complex intonational target, H+!H*, in young children (2–3 years of age) learning English. They are extending their studies of prosody to address theoretically important questions about text-to-tune alignment in other languages such as Shilluk.

The group's efforts in modeling speech production planning resulted in a publication detailing the shortcomings of the current dominant model and proposing an alternative based on phonology-extrinsic timing and a three-component process that translates abstract symbolic linguistic units (phonemes) into acoustic goals. A discussion of issues related to timing was published in *Frontiers of Psychology*.

Research in Professor Collin Stultz's Computational Cardiovascular Research 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, the MIT-IBM Watson AI Lab, and a generous grant from Quanta Computers.

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 Heldt's Integrative Neuromonitoring and Critical Care Informatics Group.

In recent work, the group has studied temporal capnography, in which the partial pressure of CO_2 in exhaled breath is recorded as a function of time. Capnograms 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 conventionally extracted and used. The group's work has provided simple physiologically based models that closely account for the observed measurements. The clinically relevant parameters estimated from these models in the course of fitting their predicted behavior to measurements have, for example, allowed effective discrimination between patients with congestive heart failure and those with chronic obstructive pulmonary disease.

This year, the group's efforts were significantly expanded through access to a public database containing volumetric capnograms, which record the partial pressure of CO_2 in exhaled breath as a function of exhaled volume. This is a more difficult modality because of the need to measure airflow, but measurements can be readily obtained from patients on ventilators—and measurements of the corresponding airway pressure are available as well.

The group's earlier models explained the new and richer data very well, more simply and quantitatively than in current methods. The new data have allowed deeper validation of the group's earlier work on temporal capnography. Their results are in the process of being prepared for journal submission, notably with two Undergraduate Research Opportunities Program (UROP) and SuperUROP students as lead authors. Efforts are under way to obtain additional ventilator data, including from COVID-19 patients.

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 demonstrated the first system to perform electrical measurements on minute volumes of blood, and those measurements were highly informative of a patient's state during sepsis. This is in contrast to existing measurements, which require more blood, take longer, and are poorly related to the patient's state.

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 (jointly overseen with co–group leader Donald Keathley) develops nanofabrication methods for applications in quantum 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.

Professor Berggren's group has developed various photodetection technologies for sensing light at extreme scales, with applications including long-range, high-speed optical communications; quantum information science and technology; and optical metrology. Key results include (1) the demonstration of nanometer-scale superconducting detectors for detecting single-photon events with a temporal resolution of a few picoseconds (a few millionths of a millionth of a second); (2) the development of single-photon detectors coupled to superconducting memory cells for photon event counting and storage; (3) photon number resolving detectors capable of distinguishing between single- and multiple-photon absorption events with high fidelity, which is critical for many emerging quantum technologies; (4) a theoretical exploration of how single-photon detectors could be used to detect dark matter interaction events; and (5) compact, integratable optical-field detectors that can directly measure the absolute phase of few-cycle optical pulses, which is critical to the stabilization of optical frequency combs for long-distance ranging and molecular sensing.

Professor Dirk Englund and his team develop computing, networking, and sensing technologies using techniques from photonics and quantum information science. In the area of quantum networks, the past year's major research accomplishments include the development of large-scale integration of artificial atoms in hybrid photonic circuits, an important step toward useful "quantum routers" that will underpin the proposed quantum internet; contributions to the first demonstration of "quantum advantage" in quantum optical communications (the first example of a photonic channel in which a quantum memory extended the reach of entanglement distribution relative to photons alone); custom complementary metal-oxide-semiconductor (CMOS) electronics for quantum control (with Professor Han); single-photon detection for microwave photons in a collaboration with BBN; and theoretical protocols for entanglement routing and quantum transduction, including one study with MIT undergraduate Yuan Lee as lead author. In the area of machine learning, major advances include new schemes for Ising solvers (with Professor Marin Soljacic) and the first study of photonic accelerators based on detailed system-level modeling (with Vivienne Sze and Joel Emer). In the area of photonic quantum computing, Englund's team demonstrated photon-photon nonlinear gates with high efficiency and low error, a scheme for resource-efficient photonic logic qubits, and a theoretical proposal and experimental demonstration of a scheme to "learn" a quantum circuit in collaboration with Google, Elenion (now Lucent), and Zapata Computing. In addition, during his sabbatical, Professor Englund co-founded QuEra Computing to develop quantum computers that show the first examples of "quantum advantage."

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. The lab has been broadening its focus to fabrics located on the most valuable real estate in the world—the surface of our bodies.

Material and processing challenges have impeded the integration of digital electronics into fibers. The group developed an approach to incorporate digital functionalities, including digital circuits, interconnections, communication protocols, sensing, memory, and algorithms, directly into thin, flexible polymeric fiber strands. They provided a scalable strategy that harnesses precise control over the positions and angles of discrete particulates within a fluid flow to connect hundreds of microscale inorganic digital chips within tens of meters of fiber in a single continuous process. The produced digital fiber strand, when worn on the body, enables large storage of body-temperature data across time- dynamic activities and on-body machine-learning inference of human activity through a deep neural network stored within the fiber. This research may open opportunities in the fields of fiber science, personal computing, and intelligent textiles.

Detection and recording of audible sound is of importance for a wide range of applications. The combination of tailoring the microstructure of a nanostructured piezoelectric transducer and controlling the fiber architectural design results in unprecedented acoustic fabrics capable of detecting and recording audible sound at a performance level on par with conventional bulky microphones. Fink's group showed a first application with a fabric that integrates three acoustic fibers enabling the detection of both direction and distance with respect to the wearer of the sound source. They then demonstrated that such acoustic fabrics serving as wearable "stethoscopes" efficiently capture cardiac sound signals, thereby permitting physiological and pathological interrogation of the human body in real time.

To date, only centimeters-long fibers with significant storage have been reported. The Fink group presented a new route: system-level fabrication of fully functional sub-kilometer-long supercapacitor fibers via a single-step preform-to-fiber thermal drawing process. They developed thermally reversible and drawable porous electrolyte and electrode gels that facilitate areal energy density of 30 $\mu Wh/cm^2$ and approximately 100% capacitance retention over 13,000 cycles. Notably, thermally drawn energy storage fibers satisfy the requirements of wearable energy solutions—flexible, high power, machine washable, usable underwater, and durable. Also, the group successfully demonstrated 3D-printed energy storage eyeglasses using a 3-m supercapacitor fiber device ink and free space optical communication through a microcontroller and diode powered by a 30-m energy storage fiber in a skirt.

Fink and his group created fibers that combine the multi-material and functional aspects they developed with tunable mechanical properties and large elasticity. The fibers are made of an elastomeric cladding, and stiff functional materials such as metal are incorporated in a helical structure by tuning the flow during the draw process or in a buckled structure by making use of the strain that is imposed to the cladding during the draw. This creates a longer pathway for the stiff material, which provides structural elasticity. The group carefully characterized this process and the different parameters controlling the final mechanical properties of the fiber. They demonstrated the applicability of this technique by connecting LED microchips with elastic electrodes inside a single fiber. The technique is potentially applicable to any type of functional fiber.

In addition, the group developed an on-demand material release platform in fiber. This represents a new capability for flexible and fabric-compatible one-dimensional systems to design and fabricate programmable and electrically controlled drug delivery fiber relying on the electric-field-driven movement of charged drug molecules. With applied DC voltage, ionic drug molecules are released from the fiber surface due to an electric field developed between the top and bottom electrodes. The release profile of drug molecules for the laser-defined gate case was demonstrated with the COMSOL simulation tool.

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

The group studied the mutual control of coherent spin waves and magnetic domain walls in a magnonic device. They experimentally demonstrated that nanometer-wide magnetic domain walls can be used to manipulate the phase and magnitude of coherent spin waves in a non-volatile manner. They developed Co/Ni multilayer films with well-defined perpendicular magnetic anisotropy, large magnetic volume, and low magnetic damping, enabling efficient coherent spin wave excitation and detection and sustained propagation over a detectable distance in a zero external magnetic field. When a domain wall was nucleated, the transmitted spin wave had a phase shift of approximately 180°, verified by micro-magnetic simulation. They further showed that a spin wave can in turn be used to move the position of magnetic domain walls via the spin transfer torque effect generated from magnon spin current. This mutual interaction between spin waves and magnetic domain walls opens up the possibility of realizing all-magnon spintronic devices wherein one spin wave signal can be used to control others by reconfiguring magnetic domain structures.

In addition, the group studied current-induced effects in the easy-plane antiferromagnet α-Fe2O3. Electrical control and detection of magnetic ordering inside antiferromagnets have attracted considerable interest in terms of next-generation magnetic random access memory. However, a full understanding of recent prototypical spin-orbit torque antiferromagnetic memory devices requires more quantitative and systematic study.

The group also studied current-induced switching in the canted antiferromagnetic insulator α-Fe2O3. They epitaxially grew α-Fe2O3 film on an α-Al2O3 substrate and deposited a thin layer of platinum to induce spin Hall magnetoresistance. Due to the uniquely small spin flop field of α-Fe2O3, they were able to control the antiferromagnetic order by a small external magnetic field and compare the current-induced Hall resistance change with the field-induced one to study the nature of the switching. Their experiment revealed that the switching signals could be complicated by two neglected sources unrelated to spin-orbit torques: the purely resistive effect and the current-induced magneto-elastic effect. The contributions from spin-orbit torques were much smaller than expected. The group's methods and conclusions are likely applicable to other easy-plane antiferromagnets such as NiO and CoO. With a deeper understanding of the current-induced effects in antiferromagnets, people can design better materials and structures for new antiferromagnetic spintronic devices.

Using physical phenomena that uniquely arise at nanometer dimensions, Professor Farnaz Niroui and her group develop new paradigms for active nanoscale devices and systems with a particular focus on emerging applications in molecular electronics, optoelectronics, and quantum technologies. To engineer such systems, which challenge the limits of state-of-the-art nanoscale processing techniques, the group develops new fabrication and metrology methodologies that provide the desired nanometer precision, resolution, and control. This is implemented through an approach integrating device physics, engineering, and materials science. During the past year, the group developed a sequential transfer printing technique relying on surface interactions for heterogeneous integration of low-dimensional materials into functional devices, the fabrication of which is not conventionally feasible. One of the applications to which they are applying this technique is a new platform for tunable plasmonic resonators wherein electromechanical reconfiguration modulates the optical response to achieve on-demand functionalities with high-resolution spatiotemporal control. They further applied the technique to develop a platform for bottom-up synthetic optoelectronics.

The group has also focused on developing a platform for studying the structure-function transformations in active molecular devices, an essential knowledge gap that has been hindering progress in the field of molecular electronics. They have used this approach to create much-needed guidelines for the rational design of practical molecular devices contributing to the field's progress from science toward technology.

Over the past year, Professor Yang Shao-Horn and his group elucidated the nature of active sites central to controlling electrocatalytic activity. Ruthenium dioxide is widely used in industrial processes and is particularly important because of its ability to catalyze a chemical reaction that splits molecules of water and releases oxygen. However, the exact mechanism that takes place on this material's surface and how that reaction is affected by the orientation of the crystal surfaces have never been determined in detail. In their recent work, the group employed surface X-ray scattering coupled with density functional theory (DFT) and surface-enhanced infrared absorption spectroscopy to examine oxygen evolution reaction (OER) on RuO_2 surfaces as a function of voltage. At OER-relevant potentials, combined surface X-ray scattering analysis and DFT results indicated an –OO group on the coordinatively unsaturated site, Ru_{CUS} of (100), similar to (110), but adsorbed oxygen for Ru_{CUS} of (101). DFT results indicated that the removal of –OO on Ru_{CUS} stabilized by a hydrogen bond with a neighboring –OH (–OO/H) could be the rate determining step for OER on (100), similar to (110), where its reduced binding on (100) increased OER activity. A further reduction in binding energy on Ru_{CUS} of (101) due to a different coordination environment of the active site resulted in a different rate determining step $[-O + H_2O - (H^+ + e^-) \rightarrow -OO/H]$ and decreased OER activity, in agreement with experimental activity. Such studies provide molecular details on active sites and the influence of their local coordination environment on OER activity, thus offering insights into the design of new catalysts for making hydrogen-based carriers from low-cost, renewable electrons to mitigate climate change challenges.

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's research program currently centers on solar cells, light-emitting devices, and spintronic switches. A recent key research accomplishment is the 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.

This year, the group focused on the development of photovoltaics (PVs) on fabric substrates and reported integration of organic photovoltaics (OPVs) into ultra-lightweight composite fabrics as a first step toward realizing electronically active fabrics. The devices are fabricated on chemical vapor deposition ultra-thin dielectric substrates, which lend themselves to fabrics through the transfer lamination process. Fabric integrated OPV devices with over 1% power conversion efficiencies have been demonstrated via standard thermal evaporation. In an effort to realize photovoltaics with higher efficiencies that can power larger electronic devices, the group is currently exploring the use of electronic polymer inks, which can be coated/printed through scalable roll-to-roll processes. Techniques developed in this project can also enable integration of other devices including displays, sensors, speakers, and actuators.

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.

The group previously had seen many examples of a thermal or mechanical impact on the gamma and X-ray emission from Co-57 on steel plates, which is a phonon-mediated nuclear excitation transfer. During the past year, they observed a reproducible delocalization effect in which excitation appears to move on the order of a millimeter or more on the Fe-57 14.4 keV transition. Mechanical placement and stability were achieved in an xy stage and measured with an optical camera, thermal stimulation was done with a resistive heater, and energy-resolved X-ray detection was done with a low-energy Amptek SSD detector.

The group is working on a quantitative evaluation of phonon-nuclear matrix elements, with a focus on the 14.4 keV transition of Fe-57. Their efforts have led to several new results. For example, in the course of upgrading their nuclear models to make use of the chiral effective field theory potential, they found that phonon-nuclear coupling is present (although not yet recognized) in these models in a form similar to what they derived years ago from the relativistic boost correction. They developed codes for multiconfigurational nuclear Hartree Fock calculations of the states that, when completed, will allow them to obtain good numbers for the phonon-nuclear interaction matrix element and off-resonant energy shift.

Professor Qing Hu and his group study terahertz quantum cascade lasers and electronics and sensing and real-time THz imaging using quantum cascade lasers and focal-plane cameras. The group has achieved many world records in terms of the performance of their THz quantum cascade lasers, including the highest operating temperature in the pulsed mode. This achievement, made during 2019–2020, was hailed by reviewers at *Nature Photonics* as "an exciting breakthrough." In addition, the group has performed real-time THz imaging at a video rate of approximately 20 frames per second, developed a novel tuning mechanism that is qualitatively different from all other tunable lasers, and 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.

Professor John Joannopoulos and Marin Soljacic work together as a team in the area of nanophotonics. They are excited about their group's recent work on a novel general theory of nanoscopic electricity and magnetism.

The macroscopic Maxwell equations, their boundary conditions, and associated local constitutive equations form the foundation of modern electromagnetic research. Although extremely successful at macroscopic scales, this foundation wholly neglects the existence of nonclassical effects (e.g., nonlocality, surface-enabled Landau damping), leading to its breakdown in the nanoscopic limit. Despite past theoretical efforts, a unified, practical theory is still absent and remains urgently sought.

Thus, the group introduced a fully retarded electrodynamic framework that naturally incorporates all of these nonclassical effects on equal footing. Specifically, they generalized the macroscopic boundary conditions to incorporate the nonclassical surface response functions known as Feibelman d-parameters, which play a role analogous to that of local bulk permittivity but for interfaces. This framework is fully general: it is applicable for modeling and understanding of any nanoscale (i.e., all relevant length scales above 1 nm) electromagnetic phenomena.

The group also made the first-ever experimental measurements of the dispersion of the complex surface response functions. By developing a quasi-normal mode perturbation theory, they cast these mesoscopic quantities into optical far-field observables, enabling measurements in designed plasmonic systems that possess pronounced nonclassical corrections. Critical results emerged: they observed surprisingly large nonclassical spectral shifts (above 30%) and the breakdown of empirical Kreibig damping. Their methodology standardizes a procedure to measure the surface response functions. This mesoscopic framework provides a new foundation for cutting-edge nanoplasmonic and nanophotonic research and establishes new connections across electromagnetism, material science, and condensed matter physics.

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 November 2019 publication in *Science*, Professor Johnson and collaborators (from Harvard and US Army labs) experimentally demonstrated the first molecular-gas THz laser with broadband tunability and compact (shoebox-sized) room-temperature operation using a quantum-cascade laser (QCL) pumping a small cavity filled with nitrous oxide to induce THz emission from rotational/vibrational transitions. Moreover, the theoretical model that predicted this result also predicted a diverse “menu” of different molecular gases that could be induced to efficiently lase over a variety of tunable frequencies using QCL pumping. Such a compact, tunable source opens up the possibility of a host of applications from imaging to secure short-range communications: by tuning the THz frequency, the propagation range of THz waves can be made to vary from meters to kilometers.

The group also developed a new theoretical upper bound to the efficiency of Raman sensing and used large-scale computational optimization to discover new structures exhibiting 100-fold improvement over conventional Raman-enhancing “bowtie” antennas. The upper bounds are the first such bounds for surface-enhanced Raman scattering (SERS): given only the material and the separation distance between the Raman molecule and the material, they predicted an upper limit to Raman enhancement for any possible shape of the material. Since the upper limits suggested that many conventional Raman structures might be deeply suboptimal, they applied "topology optimization" to search for the best possible silver structure over thousands of parameters and discovered a surprising scatterer shape that performed 100 times better than conventional SERS geometries.

Finally, Johnson and his group extended their work in optimization-based design of optical metasurfaces. With their collaborators, they demonstrated the theoretical design and experimental validation of an "extended depth of focus" metalens that could produce a diffraction-limited spot with a depth of focus several times that of a conventional lens.

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. This year's highlights included a technique to incorporate photonic integration into any advanced CMOS technology, reported by Amir Atabaki in *Nature*. This work follows the group's earlier demonstration of the first microprocessor with an optical network, also reported in *Nature*. They also used a microbioreactor to control synthetic gene networks engineered in yeast. The flexibility of this platform was demonstrated through the switchable production of two different therapeutic proteins (interferon and human growth hormone). The experiments were performed by Ningren Han (in close collaboration with Pablo Perez-Pinera from Timothy Lu's group) and reported in *Nature Communications*. Finally, the group reported the first integrated photonic platform for trapped ion quantum computing. This is the first element of a scalable architecture for integrated trapped ion quantum computing developed by Karan Mehta.

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) sources for applications in chemical detection, electron acceleration, and enhancement of space optics. Hong is a member of the technical staff of Lincoln Laboratory. He and his made good progress in a number of sub-areas over the past year, as follows.

1. Octave-spanning mid-IR source: The mid-IR range of 2 to 10 μm is called the "molecular fingerprint" region due to the abundant resonant features of the molecules, making it extremely useful for remote chemical detections. With their collaborators, the group demonstrated a novel mid-IR light source fully spanning the wavelength range from 3 to 10 μm. In particular, they developed a highly efficient optical parametric amplifier with a zinc germanium phosphide crystal using a femtosecond 2.4 μm Cr:ZnSe laser as a pump. The conversion efficiency from the pump to the mid-IR pulses was as high as 22%, the highest among mid-IR optical parametric amplifiers with ultrabroad spectral bandwidths. This offers an efficient and compact platform for a femtosecond ultra-broadband mid-IR source.

2. Femtosecond laser micromachining for X-ray telescopes: In collaboration with Mark Schattenburg's group at the Space Nanotechnology Laboratory, the group contributed to the development of a novel stress-based figure correction technique for X-ray telescope mirrors using femtosecond laser machining. They micro-machined thermal oxide layers on the back side of silicon mirrors, from which regions of intrinsic compressive stress were removed. Laser-induced integrated stress was found to increase almost linearly with the fraction of area removal in the micromachining, indicating great potential for correcting thin silicon optics by using appropriate machining parameters.
3. Long-wave infrared (LWIR) laser filamentation: The mid-IR wavelength range of 8 to 15 μm (termed LWIR) has high transmission through air with low absorption and scattering. With their collaborators, the group demonstrated LWIR femtosecond filamentation in solids, such as bulk KrS-5 and ZnSe, using femtosecond 9 μm pulses. Multi-octave supercontinuum spectra were demonstrated in both materials. In addition, 1.5-optical-cycle LWIR pulses were produced via soliton-like self-compression, confirming the experimental feasibility of high-energy, near-single-cycle LWIR light bullet generation in solids.

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 continues to make significant contributions to the development of novel quantum devices and their control. Among their key results, they found QEC codes that provide exponential savings in the number of qubits required to protect quantum information against the noise of a common random. This result promises to bring the strength of QEC to near-term devices, where it was thought not possible. The group's work was supported by a collaborative grant with Professor Englund to build quantum-error corrected repeaters.

In addition, the group identified novel quantum defects in diamond and exploited them to perform entanglement-enhanced quantum metrology, with the goal of improving the level of sensitivity beyond what is possible with classical devices. With collaborators at Harvard, they explored novel control techniques to improve the sensitivity of dense spin qubit ensembles, where the couplings dominate qubit sensor coherence, typically limiting sensitivity. By exploiting this precise control over strongly interacting systems, they were able not only to eliminate the couplings, thus increasing sensitivity, but also to engineer the couplings themselves at will.

One of the most powerful tools to protect qubits from noise and to achieve quantum simulation is to drive interacting qubits with periodic modulations. In seminal work, Cappellaro and her group experimentally probed the time scale over which such heating occurs and explored the existence of quasi-conserved quantities that can enable robust quantum operations (such as quantum computation and sensing) over exponentially long times. Such periodic driving protocols were further optimized to reach optimal fidelity in the desired, simulated evolution.

In quantum thermodynamics, the group made seminal contributions both experimentally (in a collaboration with researchers in Italy enabled by an MIT International Science and Technology Initiatives grant) and theoretically. These efforts explored the validity and extension of the Jarzynski inequality (a fundamental law akin to the second law of thermodynamics) to open quantum systems.

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. Recently, the Chuang group and collaborators at MIT 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 Quantum Coherent Electronics Group focused on developing quantum devices critical to the realization of superconducting quantum computers. In particular, they developed a coupling scheme based on a quartic potential qubit called the quarton, which results in purely nonlinear coupling. This will be important for creating improved quantum gates and microwave photon detectors. Other important results include a model to predict and improve the quantum efficiency of Josephson traveling wave parametric amplifiers and a proposal and circuit schematic for a broadband non-magnetic isolator to protect qubits from noise while allowing control and readout.

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.

During the past year, the group focused on projects related to superconducting qubits, including novel materials and fabrication, device design, high-fidelity control, noise spectroscopy, and extensions to 16-qubit chips. Specific projects addressed high-fidelity gates and the impact of environmental radiation on superconducting qubit performance.

In collaboration with partners at Lincoln Laboratory, the group demonstrated "giant" superconducting artificial atoms coupled to a waveguide. Giant atoms are qubits that are spatially larger than the wavelength of microwave light. This is a nearly inaccessible regime for natural atoms, which are angstrom sized (in comparison with the micron-scale wavelength of optical light). The group's giant atoms can emit light at one location and then reabsorb it at a second location, leading to interesting interference effects. By engineering the tunability of this interference, the group developed qubits that can be operated with high fidelity and release their quantum information as itinerant light to a microwave waveguide. This is the first step toward realizing high-fidelity quantum interconnections.

In a second project, the group asked the question What is the next “tall pole” that will limit qubit coherence? To answer this question, they collaborated with Professor Joe Formaggio (Physics) and Lincoln Laboratory to assess the impact of ionizing radiation—cosmic rays and environmental nuclear decay—on qubit performance. They used a ^{64}Cu source irradiated at the MIT nuclear reactor to calibrate the effects of varying levels of ionizing radiation on qubit coherence. They then investigated the background radiation and determined that it would limit qubits to coherence times of around 5 ms. While not limiting us today, this source of decoherence will need to be addressed to realize the full promise of quantum computation.

Professor Oliver has continued to grow these efforts and expand faculty participation. The MIT xPRO professional development courses on quantum computing, for which he is a faculty co-lead, are running continuously and have served more than 2,000 learners.

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 some significant achievements. For example, they published an invited review of quantum illumination (an entanglement-based quantum radar protocol conceived in a 2008 collaboration between Shapiro and Wong’s group and Professor Seth Lloyd’s group) in an *IEEE Aerospace and Electronic Systems Magazine* special feature on quantum radar. Quantum illumination is known to offer a target-detection performance advantage over all classical radars of the same transmitted energy despite loss and noise that destroy its initial entanglement. Their review underscored the major challenges to be overcome to obtain that performance gain in a deployable sensor and identified key failings in the experimental work being performed in Europe and Canada.

In pursuit of a novel multi-gigabit-rate quantum key distribution protocol based on frequency-entangled photons, the group constructed a 15 GHz frequency shifter using a commercially available modulator for deterministic frequency manipulation of single photons as well as classical light. In addition to potentially being an essential tool for quantum communications and quantum networks, the frequency shifter is a critical component of a new type of quantum interferometry called conjugate Franson interferometry (CFI) that can be used to measure the temporal correlation of time-energy entangled photons. The group made progress in setting up a conjugate Franson interferometer utilizing two separate frequency shifters, and its demonstration is expected to add to the growing toolbox in quantum photonics.

The group has begun retooling its table-top setup of floodlight quantum key distribution (FLQKD) to demonstrate a quantum version of low probability of intercept (LPI) in optical communication. The quantum LPI (QLPI) concept was introduced by the group and collaborators at Lincoln Laboratory as an extension of their successful FLQKD protocol to address the issue of key disclosure in encrypted messaging. Unlike classical LPI protocols, QLPI keys are transient and do not requiring sharing between the sender and the receiver of the encrypted messages. Both CFI and QLPI experiments were significantly delayed by the COVID-19 pandemic, but the group is hopeful that substantial progress will be made this year as research ramp-up continues on campus.

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. Last year the group published an *Optics Express* article containing a set of propagation primitives that properly account for specular reflections and occlusions, and this year they published two additional *Optics Express* articles greatly extending the utility of their P-field theory. The first addressed the impact of speckle on phasor-field imaging, and the second lifted the group's restrictions regarding propagation primitives so that they can be applied to the wide-angle scattering that will be encountered in most if not all NLoS imaging scenarios.

Personnel

Thomas Heldt and Vivienne Sze were promoted to the rank of associate professor with tenure. William Oliver was appointed associate professor on a one-year-to-tenure track and was granted tenure in May 2020.

RLE headquarters hired Gretchen Kindstedt in the role of fiscal officer. Susanne Patterson, fiscal officer for 12 years and recipient of the 2013 Infinite Mile Award, retired in August 2019.

Faculty Honors and Awards

Polina Anikeeva was awarded the MacVicar Fellowship in 2020.

Luca Daniel received the 2020 EECS Richard J. Caloggero Award and the 2019 Thornton Family Faculty Research and Innovation Fellowship. Also, he was nominated for the 2019 MIT Teaching with Digital Technology Award.

Dirk Englund was awarded a 2020 Humboldt Research Fellowship. In addition, he served as deputy director of the new NSF Center on Quantum Networks, a major five-year Engineering Research Center funded at approximately $20 million.

James Fujimoto received the 2019 Award of Merit in Retina Research from the Retina Society. Also, he has been awarded honorary doctorate degrees from the Fredrich Alexander University of Erlangen and the Nicolaus Copernicus University in Toruń, Poland.

Muriel Médard received a doctorate honoris causa from the Technical University of Munich and was elected to the National Academy of Engineering in spring 2020.

Kevin O'Brien was named to the Emanuel E. Landsman (1958) Career Development Chair in the Department of Electrical Engineering and Computer Science in February 2020.

Researcher Charlotte Reed received the 2020 *IEEE Transactions on Haptics* Best Paper Award.

Yang Shao-Horn was named senior editor of *Accounts of Materials Research*.

Jeffrey Shapiro received a 2019 Best Paper Award from the IEEE Signal Processing Society for "Photon-Efficient Computational 3-D and Reflectivity Imaging with Single-Photon Detectors," published in *IEEE Transactions on Computational Imaging*.

Vivienne Sze received the 2020 ACM-W (Association for Computing Machinery Council on Women in Computing) Rising Star Award.

Jacob White was named a MacVicar Fellow and won the MIT Teaching with Digital Technology Award.

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

Martin Zwierlein received the 2019 Vannevar Bush Faculty Fellowship from the Department of Defense and a 2020 Alexander von Humboldt Research Prize from the AvH Foundation.

Staff Awards

The following RLE community members won 2019 Infinite Mile Awards from the Office of the Vice President for Research: Maxine Samuels, human resources coordinator, and Sampson Wilcox, senior web and media designer, both at RLE Headquarters.

RLE Student Awards

The 2020 Helen Carr and William T. Peake Prize winner was Eric Moult, a PhD graduate student in the RLE Biomedical Optical Imaging and Biophotonics Group supervised by Professor Fujimoto. He received the award for his research on optical coherence tomography angiography–based methods to better understand the pathogenesis of age-related macular degeneration, a leading cause of blindness.

The 2020–2021 Claude E. Shannon Research Assistantship was awarded to Hyeongrak Choi, an EECS doctoral student supervised by Professor Englund. Choi was recognized for his significant accomplishments in quantum communications and quantum computing with photons and artificial atoms.

Other Student Awards

- Nicolas Arango, a PhD student supervised by Professor White, received the MathWorks Engineering Fellowship.
- Benjamin Cary, a PhD student supervised by Professor Lang, received an NIH Diversity Supplement. Despite its name, this is a competitive fellowship.
- Georgy Guryev, a PhD student supervised by Professor White, received the 2019 Magna Cum Laude Award from the International Society for Magnetic Resonance in Medicine.

- Theia Henderson, a PhD student supervised by Professor Sze, won the 2020 David Adler Memorial Thesis Award for her MEng thesis titled "A Continuous Approach to Information-Theoretic Exploration with Range Sensors."
- Justin Hou, a PhD student in Professor Liu's group, received a Mathworks Fellowship.
- Irene Kuang, a PhD student supervised by Professor White, was awarded a 2020 DoD National Defense Science and Engineering Graduate Fellowship.
- Peter Li, a PhD student supervised by Professor Sze, was the first-place winner in the graduate category at the 2020 ACM Student Research Competition Grand Finals for his paper "A Mutual Information Accelerator for Autonomous Robot Exploration."
- Anthony Tabet, a PhD student supervised by Professor Anikeeva, received the 2020 Paul and Daisy Soros Fellowship.
- Tzu-Chieh Tang received the Lemelson-MIT Student Prize in spring 2020.
- George Varnavides, a PhD student supervised by Professor Anikeeva, was awarded the 2020 Hugh Hampton Young Fellowship.
- Zhongyuan (John) Zhang, a PhD student supervised by Professor Lang, received an NSF fellowship.

Affirmative Action and Outreach Activities

In 2019, RLE's Muriel Médard 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 PIs, 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, Research Laboratory of Electronics
Professor of Electrical Engineering and Computer Science