Research Laboratory of Electronics

The Research Laboratory of Electronics at MIT (RLE) is a vibrant intellectual community and one of the Institute's earliest interdepartmental academic research centers. The mission of RLE is the furthering of 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 ground-breaking research that led to the development of ultra-high-frequency radar, a technology that changed the course of World War II. It has been home to many discoveries made in the 20th century at MIT. Cognizant of its rich history and focus on maintaining a 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 approximately $40 million in fiscal year 2021, 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 75 principal investigators (PIs). In fiscal year 2021, 275 graduate students and 114 undergraduates worked in various labs.

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

Labs and Research Highlights

The 2020–2021 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 ultracold atoms, quantum condensed gases, and atom optics. New methods are being developed for manipulating and probing Bose-Einstein condensed atomic gases and exploring ultracold interactions and collision dynamics in bosons and fermions. Additional work focuses on atom lasers, atom interferometry, atom waveguides, surface physics, and many body physics in lower dimensions, plasmas, and electromagnetics.

The research of Professor Wolfgang Ketterle focuses on many-body physics with ultracold atoms and molecules. A major goal is to assemble these building blocks to new materials and study their properties. The Ketterle group's major result during the past year was the realization of spin models using ultracold atoms in optical lattices.

The group studied spin dynamics for two different systems: ultracold rubidium and ultracold lithium atoms. With these atoms, they realized two different kinds of anisotropic spin models.

Furthermore, the Ketterle group has studied light scattering in ultracold atoms and observed for the first time, suppression of light scattering by the Pauli exclusion principle. Pauli blocking of spontaneous emission is responsible for the stability of atoms. Higher electronic orbitals cannot decay to lower-lying states if they are already occupied, which is Pauli blocking due to occupation of internal states. Pauli blocking also occurs when free atoms scatter light elastically (known as Rayleigh scattering) and the final external momentum states are already occupied. A suppression of the total rate of light scattering requires a quantum-degenerate Fermi gas with a Fermi energy larger than the photon recoil energy. This was predicted more than 30 years ago but never realized. Their paper, "Pauli blocking of light scattering in degenerate fermions" (Y. Margalit, Y.-K. Lu, F.C.i Top, and W. Ketterle; Preprint, arXiv:2103.06921), is currently under review in *Science*.

The research of Professor Vladan Vuletic focuses on quantum information processing, quantum computing, quantum measurements, 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 by the Vuletic group include the demonstration of first optical atomic clock that is enhanced by entanglement, the demonstration of a quantum simulator with a record 256 particles, 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 temperature to realize novel states of matter and to perform quantum simulations of condensed matter and nuclear physics problems. A highlight earlier this year was the creation of a quantum register of fermion pairs. The group trapped 400 pairs of fermionic atoms—those that have to obey the Pauli principle—in an optical lattice with the ability to image each atom pair individually. Quantum information is stored in the motional state of the atom pair, 0 and 1 corresponding to relative versus center of mass motion. This constitutes a nearly degenerate sub-space of states and is highly protected by the Pauli principle. We observed coherence times on the scale of ten seconds. The energy levels are split by the atomic recoil, only set by Planck's constant, the particles' mass and the lattice geometry. By increasing the interatomic interactions, the energy splitting can be tuned over three orders of magnitude, enabling 10,000 Ramsey oscillations within a coherence time. The new method opens the door towards fully programmable quantum simulation and digital quantum computation based on fermions.

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 developing multi-functional insect-scale robots and muscle-like soft artificial muscles. His group developed a 1.5-gram microrobot that uses capillary forces to climb on inverted surfaces. Compared to the state-of-the-art adhesion and climbing method, this new design improves climbing range and speed by 10 times and 4 times, respectively. This work received the 2021 Robotics and Automation Letter's Best Paper Award (five out of 2,500 submissions). They expect to use these microscale legged robots in future applications such as inspection of turbine engines and search-and-rescue.

The Chen group further developed novel dielectric elastomer actuators for microscale aerial robots. Their soft aerial robots demonstrated insect-like flight maneuvers such as in-flight collision recovery and somersaults. The agility and robustness of these soft robots exceed that of the rigid micro-aerial-robots. The work is published in the top robotics journal *IEEE Transaction on Robotics*. To share this breakthrough, ProfessorChen gave a keynote talk at a top robotics conference (ICRA 2021). This work is featured by MIT News and other news outlets. The group is continuing its efforts to develop power-autonomous insect-scale robots and hope to apply them in applications such as assisted agriculture and environmental monitoring.

The work of Principal Research Engineer Chathan Cooke, a member of the Laboratory for Electromagnetic and Electronic Systems (LEES), was in two main areas: resonant magnetic power transfer and energetic electron/photon beam interactions. For the resonant magnetic power transfer, Chathan and two graduate students in the Department of Electrical Engineering and Computer Science (EECS), Daniel Schemmel and Noah Salk, used detailed modeling and experiments to establish a validated complete "wire-to-performance" simulation tool, which accurately determines performance efficiency for a given set of transformer windings and their configuration. The primary application is for improved electronic power transformers and is supported by sponsor Prolec-GE.

The energetic radiation work uses electron and photon beams produced by the Van de Graaff accelerator facility in the High Voltage Lab. These beams continue to be applied to develop improved durability of materials for hip and knee implants. Working with satellite instrument companies, the beam has also been used to calibrate various satellite solar flux detectors.

Additionally, the beam has been used to study the possible cleaning of face masks exposed to viruses. Energetic electrons are implanted into insulators as an effective means to quantify charge transport processes. Both projects provide an opportunity to apply basic physics and circuit theory to yield improved practical devices for world-wide application in high-efficiency power systems and medical devices.

Professor James Kirtley (now post-tenure) of LEES is a specialist in electric machinery and electric power systems.

RLE graduate student Jie Mei (with support from Tommy Energy) developed artificial intelligence mechanisms for economic interchange of energy among microgrids. Matthew Overlin, another graduate student working with investigators at Lincoln Laboratory, developed and employed advanced machine learning techniques for identifying dynamic parameters of electric loads and engine generator sets for better understanding the dynamics of microgrids. Sajjad Mohammadi, also a graduate student, developed field theoretic techniques for the design of high-performance voice coil type rotary actuators and has made substantive improvements.

With support from the Office of Naval Research, RLE research specialist William Lynch, together with his graduate student Mostafa Negm, have developed balancing mechanisms. Lynch is additionally developing dynamic models of lithium ion cells to understand their dynamic performance.

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 distributed electromechanical structures.

In collaboration with Massachusetts Eye and Ear and Columbia University, the Lang group has developed implantable middle- and inner-ear microphones for fully implantable assistive hearing devices. These devices offer significant advantages: access to hearing 24/7 including during sleep, easier handling for the young and elderly, comfort during physical activities, benefit from acoustic enhancement through the external ear for improved hearing and localization, and cosmetic benefits. Over the past year they have demonstrated two different piezoelectric microphones together with their attendant low-noise amplifiers, achieving good performance on the lab bench and in cadaveric experiments.

Separately, in collaboration with Professor Bulovic, the Lang group has developed an acoustically active millimeter-thick surface comprising an array of many millimeter-scale acoustic transceivers. This surface can be scaled up to become acoustic wallpaper offering wide-area directional sound projection and reception. Applications could include directional entertainment and communication, ultrasound imaging, and noise damping and cancellation.

Professor Steven Leeb's group, the Electromechanical Systems Group, harnesses energy conversion processes. 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.

The group had an extraordinary year developing systems for controlling and generating energy. Specifically, postdoctoral staff member Kahyun Lee was accepted as a new faculty member at EWHA Women's University in Korea. US Navy lieutenant Spencer Shabshab, who completed his graduate work in the Electromechanical Systems Group, received a US Navy Commendation medal for his thesis work. Specifically, the award citation read in part: "For professional achievement in the superior performance of his duties while serving in the Navy's post graduate program at the Massachusetts Institute of Technology." In addition, the group filed a patent application and a provisional patent application on new technologies for automatic coordinated load control or self-driving loads, a new technology for demand-side energy management, and for noncontact voltage monitoring.

Professor David Perreault's research has focused on advancing power electronics technology and on the use of 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 the use of power electronics to benefit applications such as renewable energy, transportation, and industrial equipment.

One area of success this year has been the development of improved high-efficiency switched-mode circuits for industrial radio frequency (RF) power applications. Many applications, such as equipment for semiconductor processing, require delivery of RF power into highly variable loads, with increasing requirements on efficiency and bandwidth of control. One research advance has been the development of high-speed, high-efficiency solid-state tunable matching networks that enable efficient energy processing with bandwidths that are orders of magnitude faster than previously achievable. This work has led to two published journal papers and several patent filings, and has been licensed for commercial development. The underlying techniques also have implications for improving the frequency capability of a range of power electronic systems.

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

- Together with an industrial sponsor, his group is designing new non-contact handling solutions for moving semiconductor elements in 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 creating new microphysiolocigal systems for the in vitro study of human organ tissues such as brain, gut, and liver cells.
- Also in collaboration with Professor Griffith, the group is designing mechatronic solutions for new types of microphysiological systems for studying human organ tissue growth and interaction with the microbiome and immune systems on-chip.
- Professor Trumper is working with an industrial partner to design new types of magnetically levitated impellers for blood oxygenation pumping. These novel pumps have experimentally demonstrated levitation and control of pumping rotation.
- In a collaboration with MIT Lincoln Laboratory, Professor Trumper's group has designed and experimentally demonstrated a new type of levitated spherical momentum wheel for microsatellite attitude control.

Information Science and Systems

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

Up to now quantum network research has been confined to Physical Layer hardware and connection architecture. However, quantum effects will also greatly change the behavior of optical network algorithms and its network performance. Their recent exploration is a fresh look at the quantum effects of optical networking to make faint light level transactions viable. Upon re-examining of all the classical network layers that may be affected by quantum effects, Professor Vincent Chan and his group have found the familiar Media Access Control Layer (MAC) such as ALOHA and its associated "back-off algorithms" must be modified to account for quantum effects. The theoretical capacity of classical random-access networks is limited only by messaging conflicts, in which transmissions from multiple users overlap and interfere at the receiver. In the case of optical networks, the probability of successful message transmissions is further undermined by the onset of quantum errors. Even in perfect lossless channels, the measurement of light entails a non-zero probability of decoding bits incorrectly, based only on quantum statistics. They have derived the capacity of a quantum ALOHA MAC system developed in parallel to a quantum correction to the all-important classical collision "back-off" algorithm. This is the first quantum results of any higher network layers algorithms.

This year, Utsav Banerjee, a recent PhD graduate working in the MIT Energy-Efficient Circuits and Systems Group with Professor Anantha Chandrakasan, used pairing-based cryptography to enable novel security protocols suitable for Internet of Things applications, including signature aggregation and functional encryption. Banerjee's design enables two orders of magnitude energy savings through efficient hardware acceleration and algorithm-architecture co-optimizations, implements countermeasures against timing and power side-channel attacks, and provides the flexibility to implement various elliptic curve and pairing-based cryptography protocols for securing IoT networks.

Additionally, Saurav Maji, another graduate student in Professor Chandrakasan's group, also collaborated with Banerjee to assess neural networks that leak model & input information. In this work, successful side-channel based neural network model recovery attacks were demonstrated on microcontroller platforms. This was achieved using well-crafted inputs to the neural networks and observing the differences in timing and power of the operations. For recovering the inputs, they pre-characterized the system with known inputs and used this information to recover unknown inputs. The demonstrated attacks were much simpler to perform and required fewer computational resources compared to previous works. This information can be used to secure private data and prevent leaks of sensitive model and input information of embedded neural networks.

The research group of Professor Luca Daniel develops efficient scalable uncertainty/robustness quantification techniques for large/complex systems, driven by practical multidisciplinary applications (Biomedical/Imaging, Electrical Power Transmission, Nano-Transistors, Deep-Neural-Networks). Here are just a couple of representative examples this year:

Their paper on "*Dissipativity Conditions for Linearized Models of Locally Active Circuit Blocks,"* won the best paper award at the IEEE 29th Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS). This paper generalizes the concept of dissipativity of linear models to linearized models of nonlinear circuit blocks that may also include locally active behavior. They show that such models can be guaranteed to behave as dissipative and (hence guaranteed not to generate numerical instability in any system employing them), provided they are subjected to certain bounds on the small-signal input amplitude.

In previous years, they focused on generating upper bounds on the amount of perturbation any given input of a deep neural network can sustain before resulting into a misclassification. More recently, they have extended their work to generating such perturbation bounds to guarantee a given level of PROBABILITY of misclassification. This turned out to have a major impact on safety (rather than security) applications that are affected by non-adversarial noise.

This past year, much of the research in the Digital Signal Processing Group under the supervision of Professor Alan Oppenheim has focused on measurement and operating characteristics for binary hypothesis testing in both classical and quantum systems. In particular, they have developed new ways of defining and characterizing generalized measurements and the related operating characteristics for quantum systems. As part of this work, the concept of Etro spheres in operator spaces has been introduced and developed. Etro spheres play a role in measurement design for quantum systems that the Bloch sphere plays in characterizing qubit density operators. Some of this work has been reported previously at ICASSP and at the Allerton Conference and published in the corresponding proceedings. An extensive monograph on their work on both classical and quantum hypothesis testing is scheduled for publication in early 2022 in the monograph series, *Foundations and Trends in Signal Processing*. Future development and directions will include relating these theoretical developments to potential physical implementation in collaboration with Professor Paola Cappellaro and the Quantum Engineering Group in RLE.

Professor Jacob White leads the Computational Prototyping Group with Professor Luca Daniel and collaborates extensively with Professor Elfar Adalsteinsson's group on magnetic resonance imaging. The pandemic-induced isolation has shifted priorities for the group toward tasks that are more innately communal. For example, the last algorithmic advances and validation studies have been completed for MARIE 2.0, readying the software package for release to the research community. The group sought out magnetic resonance (MR) groups with complicated field manipulation challenges to drive them to complete, demonstrate, and distribute a nearly complete suite of shim coil synthesis tools.

The group's current project is the Hand-held MR Imager. Their effort is to put one of the safest and most diagnostically revealing technologies ever developed into every clinician's hands and into every student's classroom. They demonstrated they could produce MR spin-echo signals from their hand-held magnet. The next step is to start producing images using spatial encoding fields. To generate these fields, they tried using a mechanical approach by Clarrisa Cooley's work on using rotating Halbach array magnets for MR imaging but found it impractical to use in the hand-held setting. They discovered an alternative to using rotating magnet arrays by using spokes-and-hub magnets, where the encoding fields can be generated from tiny mechanical motions associated with, for example, a quarter-degree tilt along an easily processed axis. This was demonstrated, in both simulation and measurements, at the 2021 International Symposium on Magnetic Resonance in Medicine (ISMRM), after which it was selected for a finalist presentation in the ISMRM Magnetic Moments competition.

Professor Jeffrey Grossman and his team in the Grossman Group focus their efforts on the computational and experimental design of novel materials for applications in energy conversion, energy storage, clean water, and industrial separations. Significant results from this year include the demonstration of a new way to electrify graphene-based membranes, which could prevent them from fouling as well as enable new types of chemical separations. On the commercial side, Grossman's first startup, Via Separations, ran a successful large-scale pilot at a pulp and paper mill, showing both energy and cost savings by switching to Via's graphene membranes.

The group also developed a new way to protect ultrathin metal nanowire films from degrading (the key bottleneck in their commercial use) by coating both sides with graphene-based packaging, leading to record resilience (chemical, thermal, and electrical). Further, the group created a new way to extend the time in evaporative cooling layers by combining hydrogels and aerogels in a particular manner, mimicking the role of a camel's fur which strikes the perfect balance of both insulation and evaporation to keep camels cool.

Professor Jae Lim's group is involved in the development of image and video processing methods. Previously they reported a new method for more efficiently encoding images and video by reducing bits used for transmitting the side information such as the prediction direction in intra-frame encoding. During this last year, they continued their research on the new method and reported their results in "Reduction of Prediction Side-Information for Image and Video Compression" (Nissenbaum, Lucas, PhD. Thesis, January 2021). Efficient image and video compression have 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 Augusta University, the Broad Institute, MIT's Computer Science and Artificial Intelligence Laboratory, Ben Gurion University, Battelle, Bilkent University, Boston College, Boston University, Brown University, École Polytechnique Fédérale de Lausanne, Harvard University, Intelligent Automation, Intel, IBM, Hebrew University of Jerusalem, Maynooth University, Microsoft, Northeastern University, Ohio State University, Rice University, Rensselaer Polytechnic Institute, Ubiwhere, University of Aveiro, the University of California, Los Angeles, Université Catholique de Louvain, University of Coimbra, University of Massachusetts at Amherst, University of the Negev, University of New South Wales, University of Texas at Austin, Naval Information Warfare Systems Command, Technion, and the Weizmann Institute. The group's central theme is networking, with an emphasis on low delay and reliable communications. The group pioneered a noise-based decoding algorithm that promises to considerably speed up communications circuits. This work has led to developing the first ever code-universal decoding chip with new funding from the Defense Advanced Research Projects Agency. The group is the world leader in the development of network coding and is applying in fifth generation (5G) wireless systems requiring very low delays in transport protocols.

Professor Vivienne Sze works on computing systems that enable energy-efficient machine learning, computer vision, and video compression/processing for a wide range of applications, including autonomous navigation, digital health, and the internet of things. Her team had two key advances.

Designing efficient deep neural networks is a computationally challenging task. To address this need, the Sze Group developed a fast and efficient method called NetAdaptv2 that trains multiple candidate networks in parallel and introduces a method to search the depth and the width of the network simultaneously, reducing the design time by up to 5.8 times while achieving higher accuracy on a range of computer vision tasks.

One of the main bottlenecks to robot exploration speed is the complexity of computing Shannon's mutual information, which determines the next location the robot should explore and reduces the uncertainty of an unknown environment. In collaboration with Sertac Karaman, the group developed an algorithm and a hardware accelerator that reformulates the computation using a continuous occupancy map framework and that exploits the recursive structure it reveals to achieve a speedup of several orders of magnitude compared to prior state-of-the-art approaches.

Professor Gregory Wornell's research focused on localization via distributed sensors with minimal communication, selective classification with sensitivity constraints, and learning continuous pairwise Markov random fields.

For the first problem, it is well known that the source can be localized from measurements at distributed sensors provided those measurements are reliably communicated to a central processor. It was shown that, in fact, much less information is required by the processor: the group developed a novel direct position determination method based on single-bit data converters at each sensor that can achieve arbitrarily accurate estimates.

For the second problem, it was recently shown that while allowing abstentions in decision-making can improve performance, traditional mechanisms can introduce unfairness. The group established that by imposing a Markov constraint referred to as sufficiency, fairness can be restored while preserving the improved accuracy.

Finally, for the third problem, Markov random fields are important models for physical phenomena, but learning such models has traditionally been tractable only for discrete and Gaussian data. The group introduced new methods for learning such models for more general continuous data and establish their asymptotic optimality.

Professor Lizhong Zheng and his group worked 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 toward enriching analysis tools in information theory by differentiating information pieces by their content and qualities, and quantifying the overlap between different pieces with a geometric structure. Such a method is particularly useful in complex information-processing problems with multiple tasks, multi-modal data, dynamic statistics, and different forms of domain knowledge, structure, or constraints. Professor Zheng's group is involved in several projects to apply this general idea to processing information in specific applications, including in wireless communication problems, network monitoring and control systems, and more.

Some recent work from the Zheng Group has resulted in novel hybrid algorithm designs that combine the power of deep neural networks and conventional analysis-based methods, demonstrating superior performance in these applications. Professor

Zheng's efforts to incorporate his research into teaching was recognized this year by the departmental Outstanding Educator Award.

Biomedical Science and Engineering

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

In ongoing collaborations with MIT colleagues (Professors Golland, White, and Daniel), Boston Children's Hospital (Professors Grant and Gagoski), and Massachusetts General Hospital (Professors Wald and Stockmann), Professor Elfar Adalsteinsson and the Magnetic Resonance Imaging Group are pursuing imaging problems with application in human health. Among recent methodological contributions to fetal MRI are novel designs of spatially-selective RF excitations of the fetal brain by both a restricted 2D slice and 3D inner-volume selection. This approach exploits both conventional hardware—including a single-channel RF pulse and three gradient fields—and spatially non-linear fields under use control from a so-called shim array. Taken together, these magnetic fields can be jointly designed for new benchmarks of performance in restricted-slice and inner-volume excitations with the potential for enhanced imaging across a range of applications where fast image encoding of internal structures is the driving goal. A separate contribution concerns fetal motion measures by imaging for monitoring fetal health and neurological function. The group posed a method for fetal motion analysis in MRI using a deep pose estimator to extract quantitative metrics of motion from the time series of fetal pose. These tools enable the study of fetal motion to evolve with gestational age and maternal position in health and disease.

The Bioelectronics Group, led by Professor Polina Anikeeva, applies fiber-based and nanomagnetic approaches to modulate biological signaling with a particular focus on the nervous system. In the past year their group has advanced neural interfaces by creating stealthy and adaptive hybrid probes that employ hydrogels as a matrix for integration of multiple functional components. These probes have enabled stable electrical, optical, and chemical interfaces with identifiable brain neurons in behaving mice over six months old. Additionally, the group collaborated with Professor Alan Jasanoff in the McGovern Institute for Brain Research to engineer fiber-based probes for compatibility with magnetic resonance imaging in high-Tesla scanners.

The group's research in magnetic neuromodulation has motivated them to investigate the effects of magnetic fields on common biochemical reactions including the flavin mononucleotide, which is hypothesized to facilitate magnetoreception via the radical-pair cryptochrome mechanism in birds and insects. Their work has demonstrated that magnetic sensitivity of redox reactions of flavin mononucleotide is due to magnetohydrodynamic effects rather than radical-based mechanisms inviting further examination of the latter hypothesis.

Professor Louis D. Braida and the Sensory Communication Group investigate topics in three broad areas: hearing aids, the tactile communication of speech, and multisensory interactions. The major focus of their research over the past year has been the development of tactile aids for speech communication for persons with profound sensorineural hearing and/or visual impairments. This includes work on a tactile device to facilitate the communication of speech through the tactile sense alone, as well as on a tactile aid to supplement information visible on the face through lipreading. A speech-recognition algorithm was used to identify the phonemes of spoken utterances, and a set of haptic codes was created to convey information sufficient for disambiguating phonemic confusions that occur during lipreading. The haptic cues, which were presented through a seven-channel tactile display, were synchronized to the timing of the acoustic speech signals. Studies are under way for the evaluation of this tactile device as a supplement to speechreading of nonsense syllables and words in sentences. This research provides benefits not only to persons with profound sensory deficits but also has applications to virtual and augmented reality, as well as situations where normal sensory input may be compromised or overloaded with other tasks.

The research in Professor Dennis Freeman's Micromechanics Group focuses on the cochlear mechanisms that underlie the extraordinary properties of our sense of hearing, especially its sensitivity to low amplitude sounds and its acute frequency selectivity, which are hallmarks of mammalian hearing. During the past year, the group measured mechanical properties of tectorial membranes (TMs) from mice that lack functional CEACAM16 and therefore manifest progressive hearing loss. They found that TM traveling waves in adult mutant mice propagate more slowly and decay over shorter distances than those in wild-type mice, suggesting that mechanical differences of the TM underlie the behavioral deficits associated with loss of CEACAM16. They also found that traveling waves propagate more slowly in adult mutants than in juvenile mutants, suggesting a mechanical origin to the progressive nature of this mutation. A manuscript describing this work is in revision with the *Biophysical Journal*. During the past year, the group has also made substantial improvements to the Doppler Optical Coherence Microscope (DOCM) and to the algorithms that are used to reconstruct images of cochlear structures.

Up to 25% to 30% of breast cancer surgery patients require repeat surgeries because of residual cancer on the surgical margin. Professor James Fujimoto and the Biomedical Optical Imaging and Biophotonics Group developed a nonlinear microscopy technology which enables pathologists to rapidly assess surgical specimens and reduce second surgeries. They are currently performing a real-time assessment of breast cancer lumpectomy specimen margins with nonlinear microscopy—a randomized, controlled trial at the Beth Israel Deaconess Medical Center in Boston. To date, the group enrolled 45 out of 98 planned patients, 22 and 23 in the study and control groups, respectively. Positive surgical margins were found in 10 study patients, which enabled additional surgical resection in nine patients. Seven of these patients avoided repeat surgery. These preliminary results suggest that nonlinear microscopy can be used to reduce repeat surgery in breast cancer.

Research in age-related macular degeneration (AMD) is a leading cause of blindness. The group has developed ultrahigh resolution optical coherence tomography technology and are performing studies with collaborators at the New England Eye Center. They have identified high-resolution retinal structural changes that occur with early and intermediate AMD versus normal aging. These studies can help elucidate mechanisms of disease progression and assist 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 predoctoral and postdoctoral research training. In July 2016, together with her colleagues, Professor Gray founded linQ, an open organization comprising programs that seek to change the paradigm for research and training.

The key highlight for 2021 relates to the MIT Catalyst Program. Catalyst, the flagship program under linQ, has expanded. Through its partnership with the Veterans Health Administration Office of Healthcare Innovation and Learning, the MIT Catalyst program now recruits nationally, and enjoys expanded access to a major healthcare delivery organization. Additionally, they have supported the development of Catalyst Europe, which just recruited their first cohort last year. The research phase is very early, and trust they'll have research results to report in a few years.

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.

Disease manifestation and severity from acute infections are often due to hyper-aggressive host immune responses which change within minutes. Current methods for early diagnosis of infections focus on detecting low abundance pathogens (which are time-consuming) of low sensitivity, and do not reflect the severity of the pathophysiology appropriately. The approach here focuses on profiling the rapidly changing host inflammatory response, which in its over-exuberant state leads to sepsis and death. A 15-minute label-free immune profiling assay from 20 μL of unprocessed blood was developed. The hydrodynamic interactions of deformable immune cells enable simultaneous sorting and immune response profiling in whole blood. A preliminary clinical study of 85 donors in the emergency department with a spectrum of immune response states from healthy to severe inflammatory response shows a correlation with biophysical markers of immune cell size, deformability, distribution, and cell counts. The speed of patient stratification demonstrated has promising impacts in deployable point-of-care systems for acute infection triage, risk management, and resource allocation at emergency departments where clinical manifestation of infection severity may not be clinically evident as compared to patients in wards or intensive care units.

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

Research highlights over the past year include a new collaboration with MIT faculty colleagues Tamara Broderick and Vivienne Sze, colleagues from MIT Lincoln Laboratory, and active-duty personnel of the US Air Force to investigate the extent to which digital biomarkers—and particularly eye tracking metrics—can be used to improve and personalize pilot training. Additionally, Professor Heldt's team has advanced the development of ultrasound-based volumetric blood flow measurement methods for vessels supplying blood to the brain for noninvasive determination of intracranial elastance and resistance, two important measure of brain health.

Professor Timothy Lu's Synthetic Biology Group uses synthetic biology to reprogram cellular processes underlying complex biological phenomena for cellular computation, treating disease, and creating new materials. A recent gene circuit they built cumulatively triggers genetic mutations, serving to sequentially edit genomic loci and enable investigation of temporal modulation of gene expression.

To overcome antibiotic resistance, the group is engineering bacteriophages to deliver enzymes that enhance the treatment of bacterial infections. For *Shigella*, which causes severe illness in infants and children, they are evaluating engineered phages in a human intestinal organoid–derived model and targeting a virulence factor absent from commensal strains.

The group used genome-scale CRISPR screens to identify genetic perturbations that improve the survival of human cells infected by bacteria. These screens revealed routes to host-directed therapies for bacterial infections. The group is also engineering living bacteria as ingestible biosensors to detect, within the body, biomarkers of inflammatory, immunologic, and metabolic disorders. They developed an ingestible magnetic hydrogel carrier to transport diagnostic microbes to specific intestinal sites for health monitoring and sustained drug release. Finally, the group has fabricated cellulose-based living materials using a symbiotic culture of bacteria and yeast, as well as a hydrogel-based encapsulation system incorporating a biocompatible multi-layer tough shell and an alginate-based core to contain engineered micro-organisms.

The Speech Communication Group, led by Principal Investigator Stefanie Shattock-Hufnagel, is focused on developing the feature-cue-based approach to speech analysis and applying it to a range of speaker populations to test its usefulness as a tool for addressing outstanding research questions. To this end, their published studies include analyses of 1) flapped /t/ and /d/ in American English, showing that individual-acoustic-cue-based analysis reveals significant differences in phonetics among sociolinguistic groups that is not captured by traditional phonetic transcription; 2) speech by mothers to children, showing that cue-based analysis captures the geminates in Italian speech, showing that cue-based analysis resolves a long-standing debate about geminates as doubled vs strengthened consonants; and 4) Parkinsonian speech in Spanish, suggesting that individual-acoustic-cue-based analysis can reveal early onset in time to permit effective treatment. This effort in speech analysis has been supplemented by studies of speech production, including a model paper arguing that speakers plan speech using abstract phonological elements, and development for publication of new systems for labelling both co-speech manual gestures and detailed acoustic aspects of prosody (intonation and timing), enabling development and testing of more comprehensive models of speech production planning.

Professor Collin Stultz's research in the RLE Computational Cardiovascular Research Group is focused on the development and application of machine learning methods that can inform and guide clinical decision making. Over the course of the past year, the group has developed an approach to identify patients with aortic stenosis who are at high risk of death within five years after diagnosis (their method has been implemented online and made available to the medical community at large); developed a novel method for predicting the individualized effect of a given treatment on any patient; and developed and implemented methods for estimating cardiac pressures—which are typically measured using invasive procedures—from the electrocardiogram alone.

Sixian You and the Optical Imaging Group's research focuses on developing microscopy tools for biomedical applications using innovations based on optical physics, instrumentation, and algorithms. Over the past year, the group has developed a new way to image and quantitatively analyze cell dynamics in cancer progression via a combination of nonlinear optics and machine learning, all without external or genetic labels, which shows potential for clinical translation. These results were published in *Cancer Research*, and the group open-sourced the images and codes for wider dissemination of the technique. Recently, they started to work on new ways to deliver and retrieve light deep into tissue so that they can potentially maintain all the good things associated with microscopy (high resolution, contrast of living cells) and overcome the fundamental limitation of depth penetration (tissue surface only).

Research in RLE's Computational Physiology and Clinical Inference Group directed by Professor George Verghese has focused in recent years on capnography, which records the partial pressure of CO^2 in exhaled breath as a function of time or of expired volume. Temporal capnograms are ubiquitously recorded in hospital settings, providing a noninvasive and effort-independent monitoring modality. The recording of volumetric capnograms is more involved because of the need to capture and measure exhaled airflow, but this data is readily obtained from patients on ventilators. The group's work has provided simple physiologically based models that closely account for both categories of capnogram. The clinically relevant parameters estimated from these models in the course of fitting their predicted behavior to measurements have application to screening, diagnosis, and monitoring for cardiorespiratory conditions. Data from ventilated patients has now permitted the group to validate their earlier theoretical finding that temporal capnography allows estimation of the entire exhaled airflow profile to within a scaling. The airflow profile is revealing of the state of the lungs and can form the basis for distinguishing between, for instance, chronic obstructive pulmonary disease and congestive heart failure. The group has now shown that the scaled profile can be used similarly.

Professor Joel Voldman's research interests focus on BioMEMS (biomedical microelectromechanical systems), 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 in immunology. Professor Voldman's group has been developing systems able to measure protein levels in minute quantities of blood in just a few minutes. They have demonstrated the incorporation of full upstream processing, from blood acquisition all the way to measurement readout. This has been supplemented with descriptive models of the system that have enabled optimization of performance and thus reduction of operating time.

Nanoscale Materials, Devices and Systems

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

The Quantum Nanostructures and Nanofabrication group, led by Professor Karl Berggren with co-group leader Dr. P. Donald Keathley, has efforts in the following areas: (1) superconducting nanotechnologies for radiation detectors, quantum circuits, and superconducting nanoelectronics; (2) nanoscale field emitters for the investigation of strong-field physics and the development of ultrafast nanoelectronics and low-voltage vacuum electronic devices; (3) nonlinear optical and electronic devices that leverage nanostructured materials to enable new device architectures and improve performance; and (4) the investigation of fundamental interactions of electrons, ions and photons with matter for applications in lithography, microscopy, light generation and nanofabrication. Key results in the past year include the development of optical field sampling detectors with attosecond resolution that could be used to improve the detection of biomolecules or reveal ultrafast energy transfer dynamics important to photosynthesis and photovoltaics, and the realization of a superconducting spiking nanowire device capable of efficiently forming neural networks.

Professor Dirk Englund and the Quantum Photonics Laboratory develop communications, computing, and sensing technologies primarily in the fields of semiconductor optics and quantum information science. Each area saw significant progress over the past 12 months. Advances in communications include the kick-off of the NSF Center on Quantum Networks, of which Englund is deputy director; schemes for networking superconducting quantum computers; and experimental breakthroughs in photonic circuit-based quantum repeaters with more than 100 memory qubits. Progress in computing include large-scale photonic control for cold-atom quantum computing with Center for Ultracold Atoms collaborators and novel quantum machine learning systems, as well as programmable optical systems for machine learning acceleration with a particular set of breakthroughs showing the feasibility of near-perfect error correction against hardware imperfections. Major advances in sensing technologies include single-photon-sensitive bolometry using dilute electron gases in the microwave and near-infrared spectrum, advanced solid-state quantum sensors, and understanding atomic Brownian in optical nanocavity resonators. Englund also continued his technical advising roles with the US Department of Energy in quantum information science and with spin-out companies Dust Identity, LightMatter, and QuEra Computing.

Professor Yoel Fink and his research group focus on extending the frontiers of fiber materials from optical transmission to encompass electronic, optoelectronic, and acoustic properties. Exposed to troves of data, important health insights would be revealed if fabrics could compute, sense, store, analyze, infer, alert, and act while retaining their traditional qualities. This year, a new course on computing fabrics was developed and taught in collaboration with the Rhode Island School of Design. When worn on the body, digital fiber strands enable 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. In acoustic fibers, the team developed ultralong, highly uniform, flexible fibers that can serve as mobile fabric-based microphones via a simple and scalable preform-to-fiber approach, demonstrating that such acoustic fabrics, serving as wearable stethoscopes, can efficiently capture cardiac sound signals, permitting physiological and pathological interrogation of the human body in real time. They successfully demonstrated 3D-printed energy storage eyeglasses using a 3m supercapacitor fiber device. Additionally, they demonstrated the applicability of elasticity in fibers by connecting tens of LED microchips with elastic electrodes inside a single fiber. This technique may then be applied to any type of functional fiber. A concerted effort on building an entire computer in a fiber is reaching its culmination and work is under way to establish the first fiber computer.

Professor Luqiao Liu and his group's research has been focused on investigating novel spintronic devices and materials. The group has studied the spin transport phenomena inside antiferromagnets, which revealed the possibility of using antiferromagnet as building material for magnonic devices. Antiferromagnets (AFMs) possess great potential in spintronics because of their immunity to external disturbance. The coupling of insulating AFMs to spin-orbit materials enables spin transport via AFM magnons. Particularly, spin transmission over several micrometers occurs in some AFMs with easy-axis anisotropy. Easy-plane AFMs with two orthogonal, linearly polarized magnon eigenmodes own unique advantages for low-energy control of ultrafast magnetic dynamics. However, it is commonly conceived that these magnon modes are less likely to transmit spins because of their vanishing angular momentum. In their recent work, the group showed the experimental evidence that an easy-plane AFM, a α-Fe2O3 thin film, can efficiently transmit spins over micrometer distances, which is further explained by the interference effect of two linearly polarized propagating magnons. Furthermore, their devices can realize a bi-stable spin-current switch with a 100% on/off ratio under a zero remnant magnetic field. These findings provide additional tools for nonvolatile, low-field control of spin transport in AFM.

Engineering matter deterministically at the atomic scale into designer materials and devices with unconventional functionalities is critical to enabling next-generation nanoscale and quantum technologies. Despite tremendous efforts, such precise engineering has largely remained inaccessible. By developing new design, metrology, and processing platforms—through the research of Professor Farnaz Niroui and her research team—the group addresses these limitations to uniquely access, study, and manipulate the extreme nanoscale dimensions and develop new paradigms of active nanoscale devices and systems. The team's research during the past year has developed a platform for on-site growth of designer quantum emitters based on halide perovskite nanocrystals for on-demand single photon emission with controlled light-matter interactions. The resulting emitters can help achieve deterministic and indistinguishable, yet easily processible and tunable, single photon sources that have long been desired as building blocks for quantum information technologies. Utilizing engineered surface interactions, the team has also developed new additive fabrication techniques to enable precise yet high-throughput integration of low-dimensional materials into device designs with pristine and controlled interfaces. This helps address one of the most fundamental limitations that impede experimental realization of some of the new device concepts and their transition into practical technologies.

Professor Yang Shao-Horn's recent work has revealed that regulating surface oxygen activity, defined as O2 p-band center relative to the Fermi level, can tune the adsorption energetics of NOx and the kinetics of NO oxidation for oxides. Increasing surface oxygen activity can not only promote stronger adsorption of NO, enhancing the kinetics of NO oxidation, but also can poison the oxide surface with more adsorbed nitrogen-like species, impeding the kinetics, rendering a volcano trend for the NO oxidation kinetics as a function of the surface oxygen activity. Such design principles provide new strategies to design novel metal oxides with enhanced activity and functions for mitigating environmental and atmospheric pollution. In addition, their recent work demonstrates an Li-metal battery technology that can store energy up to two times that of Li-ion. This technology advance stems from electrolyte innovations, where newly discovered liquid electrolytes are shown to enable stable cycling of high-energy nickel-rich materials and lithium metal, replacing graphite used in Li-ion batteries. These Li-metal batteries offer many advantages to scalability over ceramic Li-metal battery technologies as the new electrolyte can be a drop-in replacement in commercial Li-ion and Li-metal batteries.

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 their demonstration of coupling between silicon solar cells and singlet exciton fission in the molecular semiconductor tetracene. Originally proposed by Dexter in the 1970s, this coupling promises to increase the maximum efficiency of silicon solar cells to 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 for this coupling was studied extensively this year and shown to rely on defect states in hafnium oxynitride. A new rationally designed interface is under development and will be the subject of future work.

A second result is the stabilization of organic light-emitting molecules by tuning the excited state lifetime. The 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. Here, the researchers demonstrate 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, corresponding to a nearly quartic dependence. 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. During the last year, we demonstrated OLEDs that exhibit Purcell effects exceeding a factor of three, combined with high external quantum efficiency (>25%), and promising stability benefits relative to control devices.

The technical research of Professor Vladimir Bulović and his group encompasses the study of physical properties of nanostructured thin films, interfaces, and devices. This year, the OneLab developed a new molecular platform for fast low-voltage nanoelectromechanical switching. The modular nano-scale mechanical switch is based on a tunable molecular gap between atomically-smooth bottom electrodes and a conductive nanoparticle top contact. Modulating the gap electromechanically by ~1 nm leads to a more than five orders of magnitude contrast in the tunneling current through the molecular junction. This unique mechanism enables the nanoswitch to simultaneously demonstrate a low turn-on voltage (under 3 V) and an extremely high switching speed (2 ns turn-on delay), which has not been achieved previously. Such high performance is also attributed to two degrees of design freedom in their device architecture, namely the steric effects in the junction molecules and the structure of the nanoparticle, which allows the group to tailor the static and dynamic behavior of the nanoswitch independently. The lab also experimentally showed that the I-V characteristic is determined by the selection of junction molecules, while the turn-on delay can be modulated by the choice of nanoparticle, which functions as the nanostructured moving contact. Numerical analysis indicates that the performance of these devices can be further improved with refined nanoswitch components and may be able to demonstrate sub-1-V and sub-1-ns switching.

Professor Peter Hagelstein and his group's phonon-nuclear interaction model was derived anew from a Bethe-Salpeter model. A non-relativistic reduction in the case of one-pion exchange with pseudovector coupling was done, and a reduction of the spin, isospin, and angular momentum was done for the HD/^{3}He phonon-nuclear coupling matrix. New codes were developed for kinetic energy and nuclear potential models for a multiconfigurational model to be used for phonon-nuclear coupling. Currently, a model for three-nucleon systems is being develop for phonon-nuclear coupling. The group has understood how excitation transfer from the HD/^{3}He system can accelerate ^{137}Cs decay.

The researchers found an error in the experimental xz-stage ^{57}Co/^{57}Fe excitation transfer results mentioned in last year's input, which has prompted a focus on a new kind of experiment in which resonant excitation transfer is predicted to lead to beam formation in a near single crystal sample. The team's concept paper on their excitation transfer theory and new experiments for an ARPA-E (Advanced Research Projects Agency–Energy) competition was selected. The group has understood that the energetic ion signals in the deuteron beam experiment on Ti is due to high-Z impurities, which points to new experiments with doped samples and new high-Z samples.

Principal Research Scientist Kyung-Han Hong leads the development of novel ultrafast mid-infrared (mid-IR) sources and IR sensors. Hong's main affiliation is Lincoln Lab as a member of the technical staff. He and his group made a progress on a number of sub-areas this past year.

- High-power ultrabroadband mid-IR laser source. With support from the US Department of Energy and Lincoln Laboratory, Hong's group developed a novel high-power femtosecond mid-IR light source fully spanning the wavelength range from 3 to 10 mm, which is suitable for chemical detections and environmental monitoring.
- Electrically wavelength-tunable IR detectors. Funded by Lincoln Lab in collaboration with Long Ju's group in the Physics Department, the group has fabricated electrically tunable, graphene-based IR detectors and demonstrated proof-of-principle spectrometer-free chemical detections. This collaboration effort is being expanded to bigger programs for applications to hyperspectral IR imaging and on-chip IR spectroscopy on a satellite.
- Mid-IR laser filaments. The group reported the highest-energy mid-IR laser filamentation in solids along with multi-octave-spanning supercontinuum generation, covering from the visible to ~5 mm wavelength range. This is a promising source for studying mid-IR nonlinear dynamics as well as seeding high-power mid-IR laser amplifiers.

Professor Qing Hu and his group study terahertz quantum cascade lasers and electronics, as well as sensing and real time THz (T-rays) imaging using quantum cascade lasers and focal-plane cameras. His group has achieved many world records in terms of performance of their THz quantum cascade lasers, including but not limited to the highest operating temperature in the pulsed mode ~250 K. This achievement was hailed by reviewers at *Nature Photonics* as "an exciting breakthrough" and "a major milestone for THz photonics." He and his group performed real-time THz imaging at a video rate of ~20 frames/second. They have developed a novel tuning mechanism that is qualitatively different from all other tunable lasers and have achieved continuous tuning over a broad frequency range (~330 GHz). More recently, the group has developed the first THz laser frequency combs and demonstrated dual-comb spectroscopy. These are experiments with the potential to lead to improvements in sensing, imaging, and high bandwidth communications. In 2020–2021, they developed and delivered local oscillators for the OI spectral line at 4.74 THz for the GUSTO (GUSTO: Gal/Xgal U/LDB spectroscopic-stratospheric terahertz observatory) program. This ultra-long duration (more than 100 days) balloon-based THz observatory will be launched at the end of 2021. The extensive mapping of the OI line will provide information and shed new light on star and galaxy formation.

Professors John Joannopoulos and Marin Soljacic work together as a team in the area of nanophotonics. They are excited to report about their group's recent work. The Hofstadter model, well known for its fractal butterfly spectrum, describes two-dimensional electrons under a perpendicular magnetic field, which gives rise to the integer quantum Hall effect. Inspired by the real-space building blocks of non-Abelian gauge fields from a recent experiment, the researchers introduced and theoretically studied two non-Abelian generalizations of the Hofstadter model. Each model describes two pairs of Hofstadter butterflies that are spin–orbit coupled. In contrast to the original Hofstadter model that can be equivalently studied in the Landau and symmetric gauges, the corresponding non-Abelian generalizations exhibit distinct spectra due to the non-commutativity of the gauge fields. The group derived the genuine non-Abelian condition for the two models from the commutativity of their arbitrary loop operators. At zero energy, the models are gapless and host Weyl and Dirac points protected by internal and crystalline symmetries. Double (8-fold), triple (12-fold), and quadrupole (16-fold) Dirac points also emerge, especially under equal hopping phases of the non-Abelian potentials. At other fillings, the gapped phases of the models give rise to topological insulators.

Professor Steven Johnson's work with the Nanostructures and Computation Group focuses on the development and application of computational-design techniques for optical "metalenses," ultra-thin nano-patterned surfaces that can mimic the functionality of bulky lenses. The group has shown that metalenses can perform functions that go far beyond the capabilities of traditional lenses. By combining the metalens design process with computational image processing, they have shown that end-to-end devices can be designed for optical polarimetry, super-resolution imaging, and spectroscopy tasks. By incorporating the design freedom of nanoscale 3D printing, they showed that metalenses can simultaneously focus widely separated wavelengths, such as near and mid-wave infrared, eliminating the need for separate lenses when working with ultra-broadband imaging. The group also demonstrated the first metalens "plan-achromat" design, which simultaneously focuses many angles and wavelengths without chromatic or angular aberration. Moreover, their computational efforts drove the development of new algorithms in machine learning for deep surrogates—in training a neural network to mimic the behavior of slow physics simulations, they showed how active learning can be used to adaptively choose the simulation parameters and speed up the training by a factor of 10 or more.

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

Highlights this year include a new way of making large sheets of high-quality atomically thin graphene that could lead to ultra-lightweight flexible solar cells and to new classes of light-emitting devices and other thin-film electronics using an intermediate carrier layer of material after the graphene is laid down through a vapor deposition process. The carrier allows the ultrathin graphene sheet—less than a nanometer (billionth of a meter) thick—to be easily lifted off a substrate, allowing for rapid roll-to-roll manufacturing. Another highlight is the use of atomically thin materials (instead of silicon) as the basis for new transistors. Connecting these 2D materials to conventional electronic components is difficult. The group, along with other researchers, have found a new way of making sch electrical connections, which could unleash the potential of 2D materials and further the miniaturization of components—possibly enough to extend Moore's Law.

Professor Rajeev Ram and the Physical Optics and Electronics Group invents new optoelectronic devices to solve problems in communications, energy, and bioengineering. Their research focuses on the boundary of systems and device physics. The systems drive the need for creative solutions and validate the utility of scientific research. One area of current research focuses on developing photonic technologies to address climate change. Two papers published in *Frontiers in Plant Science* and *Scientific Reports* demonstrate that Raman spectroscopy can be used to guide precision delivery of nitrogen fertilizer, thus limiting runoff of excess nitrogen, which is a major source of pollution for aquatic ecosystems as well as a major source of greenhouse gases produced during the manufacture of ammonia. A perspective on how such new sensor technologies can support sustainable farming has been published in *Nature Plants*. The group continues their research in advanced CMOS (complementary metal-oxide semiconductor) technology and in synthetic gene networks engineered in yeast using a microbioreactor.

Quantum Computation and Communication

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

Professor Paola Cappellaro's Quantum Engineering Group focuses on developing novel quantum devices by engineering quantum systems and their control. The research activities span the control of small quantum systems optimized for specific tasks, such as quantum sensing, and of larger many-body systems that provide a platform to study quantum simulation and, more broadly, limits on the control and coherence of scalable quantum systems.

Among key results, the group found novel control sequences to increase the coherence time of spin qubits and allow vector magnetometry with single spins, while most previous schemes only allowed scalar magnetometry. The exquisite control on such systems also enables their use for quantum simulations of exotic matter states, such as tensor monopoles and time symmetries. By advancing the control of many-body systems with analytical, and machine-learning optimization, they were able to explore the Floquet prethermalization regime (a robust phase that emerges under periodic driving of many-body quantum systems) and the rate at which this quasi-equilibrium phase will eventually thermalize—an important benchmark in the quest to control ever-larger quantum systems.

Professor Isaac Chuang's group studies theoretical and experimental quantum information science, and seeks to harness the laws of quantum physics to solve hard problems faster than is possible with conventional classical computers. The group is currently building a new cryogenic vacuum apparatus for performing experiments with metastable qubits, which offer a flexible platform for achieving high-fidelity quantum gates. They're also working on a scheme to store quantum information in the quantum oscillator modes of trapped ions in order to enable dense packing of data into just a few ions. Both of these projects take advantage of their strong collaboration with the trapped ion team at Lincoln Laboratory, enabled via the Center for Quantum Engineering. On the theory side, the group looks for simplicity, whether in their development of novel instantiations for the algorithmic primitive of quantum signal processing, their explorations of continuous variable quantum computing, or fundamental work in quantum information. Theory is often motivated by the intuition and resource constraints of experiment; they continue to look toward applying the techniques or engineering, sensing, or adversarial models to theoretical results to motivate new and useful subfields in quantum information.

Professor Kevin O'Brien leads the Quantum Coherent Electronics group, which continued in their research direction of developing key technologies for scalable superconducting quantum computers. Their theoretical proposal for a "purely nonlinear coupler" which avoids the deleterious linear interactions and may lead to faster readout and two-qubit gates, was published in *Physical Review Letters*. Toward the aim of improving quantum limited amplifiers, the group identified higher order modes as the dominant source of noise in existing traveling wave parametric amplifiers and proposed a solution of adiabatically varying the nonlinearity of the device versus position to always remain in a Floquet mode and recover the information previously lost to higher order modes. These near ideal quantum amplifiers have broad applications to sensitive microwave measurements in quantum computing, dark matter searches, and cosmology. Their proposal for a broadband non-magnetic isolator to protect qubits from noise while allowing control and readout was submitted for publication. They are working with Lincoln Laboratory to realize these devices.

Professor William D. Oliver, Professor Terry Orlando, and Research Scientist Simon Gustavsson and Joel Wang direct the Engineering Quantum Systems (EQuS) group, a multi-disciplinary research effort 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.

This past year has been quite successful for the EQuS group. They have published 19 manuscripts and currently have another 12 manuscripts posted on the quantum physics arXiv. They have demonstrated state-of-the-art two-qubit gate fidelities at the 99.9% level for both CZ and iSWAP gates. These gates are now being used in demonstrations of quantum simulations. The group has grown to six postdoctoral associates, 17 graduate students, and six undergraduates. Gustavsson returned from his leave of absence after his start-up company had been acquired by Keysight Technologies.

Professor Jeffrey H. Shapiro and Dr. Franco N.C. Wong work on theory and experiments related to reaching ultimate limits in communication, imaging, and precision measurements at optical frequencies. This year, the group had some significant achievements. First, they published three major theory papers in *Optics Express* that greatly advance the understanding of phasor-field imaging, a new technique for seeing around corners by means of diffuse reflections. Second, in *Physical Review Applied* and *Optics Express*, they reported theoretical results for the secret-key rates of quantum key distribution (QKD) systems operating over free-space optical links. Among other things, these results show that QKD using simpler-to-implement focused-beam arrays provide better robustness to the ill effects of atmospheric turbulence than the widely touted orbital angular momentum beams. Finally, there was great progress in their collaboration with researchers at the University of California at Los Angeles on a program to develop a novel multi-gigabit-rate QKD system based on frequency-entangled photons. Using the optical frequency shifter they developed last year and described in a 2021 *Scientific Report*s publication, they have just completed and demonstrated the world's first conjugate Franson interferometer (CFI). The CFI, which will be used to secure the frequency-entangled QKD link, is a major new addition to the quantum-measurement toolbox.

Personnel

RLE Headquarters promoted Kenneth Luu to the role of fiscal officer.

Faculty Honors and Awards

- Kevin Chen received the 2021 Robotics and Automation Letter's Best Paper Award.
- Luca Daniel was awarded the Richard J. Caloggero Award from EECS in 2020.
- Dirk Englund received the 2020 Alexander von Humboldt Fellowship.
- James Fujimoto received the Greenberg Visionary Prize in December 2020 along with Dr. David Huang, MD, PhD (former HST student) and Eric Swanson (RLE affiliate) for research to eradicate blindness.
- Peter Hagelstein received the Jerome H. Saltzer Award for Excellence in Teaching in EECS in July 2020.
- Thomas Heldt was promoted to rank of associate professor with tenure and appointed a visiting professor at ETH Zürich.
- Luqiao Liu was awarded the Sloan Research Fellowship in February 2021.
- Muriel Médard was elected in 2021 to the American Academy of Arts and Sciences and received the 2021 IEEE Kingo Kobayashi Computers and Communications Award.
- Jelena Notaros received the the Forbes 30 Under 30 award and MIT RLE Early Career Development Award.
- William Oliver was promoted to professor in the Departments of Electrical Engineering and Computer Science and in Physics.
- David J. Perreault was elected to the National Academy of Engineering in 2021 and received the IEEE Journal of Emerging and Selected Topics in Power Electronics 2nd Prize Paper Award for the paper "High Frequency Inverter for Variable Load Operation" in 2021.
- Yang Shao-Horn received the Humbdolt Research Prize in Chemistry, the Dr. Karl Wamsler Innovation Award from the Technical University in Munich, and an award from the National Academy of Inventors, all in 2020.
- Collin Stultz was awarded the Phi Beta Kappa Visiting Scholar and received the Nina T. and Robert H. Rubin Professorship in 2021.
- Sixian You received the Amazon Research Award, the Scialog Fellow and Award (RCSA, Advancing Bioimaging) and the Alfred Henry and Jean Morrison Hayes Career Development Professorship at MIT, all in 2021.
- Jacob White was named a 2020 MacVicar Faculty Fellow in EECS.
- Gregory Wornell received the 2021 School of Engineering Ruth and Joel Spira Award for Distinguished Teaching.
- Lizhong Zheng received the MIT EECS 2021 Outstanding Educator Award.

Staff Awards

Edwin Pedrozo-Penafiel, postdoctoral associate in the Vuletic Group, won third place in the PDA MIT symposium.

Carlos Errando Herranz, working in the Englund group, received the 2020 Marie Curie fellowship.

Bevin Huang, member of the Englund group, was awarded the 2021 Intelligence Community postdoctoral fellowship.

Nicholas Harris, PhD 2017, working with Professor Englund, was awarded the 2021 MIT TR35.

Maria Eugenia Inda, working under Professor Timothy Lu, was the recipient of many awards this year: nominated for the Regeneron Prize for Creative Innovation 2021, awarded the Langer Prize for Innovation and Entrepreneurial Excellence (2020), appointed as Topic Editor for Biosensors, selected as a finalist for the inaugural postdoctoral symposium held by the MIT Postdoctoral Association in June 2021, and selected as a finalist for the New England Science Symposium in April 2021.

Anuran Makur, a recent graduate student supervised by Professors Lizhong Zheng and Yury Polyanskiy, won the 2021 Thomas Cover PhD Dissertation Award from the IEEE Information Theory Society for his thesis, "Information Contraction and Decomposition."

Shota Nakade, working with Professor Tim Lu's group, received the Uehara Memorial Foundation Overseas Postdoctoral Fellowship.

Student Awards

The 2021 Helen Carr and William T. Peake Prize winners were:

- Meenakshi Asokan, a Harvard student working in the Eaton Peabody Laboratories at the Massachusetts Eye and Ear Infirmary under the supervision of Professor Daniel Polley, for her work in vivo calcium imaging and multi-regional single unit recordings to study neural communication between different hierarchical stages of sound processing in the brain
- Tzu-Chieh (Zijay) Tang, a student in the Synthetic Biology Group of Professors Timothy K. Lu and Neri Oxman, for his work using engineered microorganisms to build living functional materials that sense and respond to their surrounding environment
- Jimin Park, student in the Bioelectronics Group, supervised by Professor Polina Anikeeva, for his research that combines nanomaterials chemistry, electrochemistry, and neural engineering with the goal of understanding chemical signal transduction in the nervous system

The 2020–2021 Claude E. Shannon Research Assistantship was awarded to Marco Colangelo for his research that focuses on advancing superconducting nanowire technology for photon detection and microwave signal processing. He is a graduate student in the Quantum Nanostructures and Nanofabrication Group, supervised by Professor Karl Berggren.

Other Student Awards

- Marco Colangelo, supervised by Professor Karl Berggren, was awarded the RLE Claude E. Shannon Fellowship and the IEEE Council on Superconductivity Fellowship.
- Owen Medeiros, supervised by Karl Berggren, was awarded the Department of Defense National Defense Science and Engineering Graduate Fellowship.
- Emma Batson, supervised by Karl Berggren, was awarded the National Science Foundation Graduate Fellowship.
- Aziza Almanakly, supervised by Professor William Oliver, was awarded a P.D. Soros Fellowship and the Clare Boothe Luce Fellowship.
- Junyoung An, supervised by William Oliver, was awarded the Korea Foundation of Advanced Study Fellowship.
- Jonathan Birjiniuk, supervised by Professor Thomas Heldt, received a Takeda Graduate Fellowship in 2021.
- Benjamin Cary, supervised by Professor Jeffrey Lang received and National Institutes of Health Diversity Fellowship in 2020.
- Isabelle Cunitz, supervised by Professor Yang Shao-Horn was accepted to the 2021 Global Young Scientist Summit.
- Leon Ding, supervised by William Oliver, was awarded the IBM Fellowship.
- Dimitrios Fraggedakis, co-advised by Professor Martin Bazant in Chemicak Egineering and Professor Shao-Horn, was the Silver Finalist, 2020 MRS Fall Meeting, and was awarded a Miller Postdoctoral Fellowship at the University of California at Berkeley.
- Ami Greene, supervised by William Oliver, was awarded the Google Fellowship.
- Linsen Li, supervised by Professor Dirk Englund, received the 2020 QISE-NET TRIPLET AWARD
- Naomi Lutz, a UROP undergraduate supervised by Yang Shao-Horn, was awarded the Carl G. Sontheimer Prize by Mechanical Engineering.
- Thomas Propson, supervised by Dirk Englund, received the 2020 NSF GRFP.
- Hamza Raniwala, supervised by Dirk Englund, was awarded the 2021 NSF GRFP and received the 2021 NDSEG Fellowship.
- Noah Salk, supervised by Principal Investigator Chathan Cooke, was awarded the 2020–2021 Landsman Fellowship Fund.

- Lieutenant Spencer Shabshab, supervised by Professor Steven Leeb, received a US Navy Commendation medal for his thesis work.
- Yixuan (Cassie) Song, supervised by Dirk Englund, was awarded the 2020 MIT Robert M. Rose Presidential Fellowship.
- Michael Stolberg, supervised by Yang Shao-Horn, won Best Poster award at ACS Spring 2021.
- Madison Sutula, supervised by Dirk Englund, received the 2020 NASA NSTGRO Fellowship.
- Jennifer Wang, graduate student advised by Professor Kevin O'Brien, was awarded the Doc Bedard Fellowship.
- Daniele Vivona, supervised by Yang Shao-Horn, was awarded a 2021MIT Energy Fellowship.
- Bright Ye, graduate student and Jennifer Wang's teammate, supervised by Kevin O'Brien, won an IBM Quantum Awards Open Science Challenge prize.
- Yang Yu, supervised by Yang Shao-Horn, was awarded the ECS Battery Division Student Award 2021.
- John Zhang, supervised by Jeffrey Lang, is a continuing NSF Fellow.
- Yirui Zhang, supervised by Yang Shao-Horn, was accepted to 2020 ME Rising Stars Workshop. hosted by UC Berkeley, and to the 2021 Global Young Scientist Summit.

Affirmative Action and Outreach Activities

Nothing is more innately communal than education. With that in mind, Professor Jacob White and his group's "Hands-On for Half Price" effort (very-low-cost kits of sophisticated and pedagogically effective design experiences) has already become pervasive at MIT. The kits are being used in the Department of Aeronautics and Astronautics in EECS; 500 kits were shipped to 8.02 students this past spring. The next step is to try using "kit-expertise" to enhance outreach, so kits were developed that could be useful in teaching feedback control (via Zoom) to high school students. This past July, the kits were used to teach control to 22 Caribbean high school students, who—even though they were spread out across a half-dozen islands—managed to build four control systems, including a difficult-to-stabilize magnetic levitator. The course was taught in collaboration with Professor Warde and Dr. Sah, and as part of their SPISE program. The SPISE control class was generally successful, but now that more is known, 50 kits are being prepared for use in control classes at Bayero University in Nigeria in spring 2022 in collaboration with EECS Professor Tayo Akinwande.

Additionally, Professor Muriel Médard and the Network Coding and Reliable Communications Group is working on machine learning fairness for STEM (Science, Technology, Engineering, and Mathematics) education for women, for health care, and for creating fairness for loan applications.

Speical Note on Research during the Pandemic

The previous year has presented remarkable challenges for research in RLE, especially experimental work. On behalf of all my colleagues, as well as the graduate students, postdoctoral scholars, and research scientists, I express my enormous gratitude and admiration for the resourceful response of our staff. Our human resources and fiscal teams efficiently transitioned to remote work, while the RLE facilities and information technology teams maintained the physical infrastructure. In addition to Environmental Health and Safety Representative Marie Gentile, the professional dedication of our facilities and Information Technology Group kept our laboratories operating. These efforts allowed RLE to persevere in its mission. For many of us, their efforts allowed us to continue our lives, finalize PhD theses, and complete experiments that represent the culmination of years of effort.

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