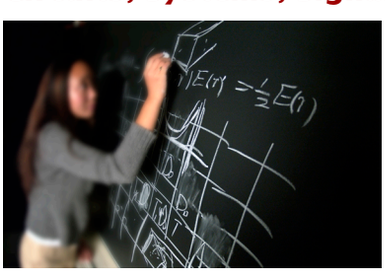
Research Laboratory of Electronics

The Research Laboratory of Electronics (RLE), founded in 1946, is the Institute's first interdisciplinary research laboratory. RLE grew out of the wartime MIT Radiation Laboratory and was formed to bring together physicists and electrical engineers to work on problems in electromagnetic radiation, circuits, and specialized vacuum tubes. Over the years, RLE's research interests have branched in many directions so that today it is the most intellectually diverse of MIT's interdisciplinary research laboratories. Research within RLE today is conducted by approximately 50 faculty members affiliated with the departments of Biological Engineering, Electrical Engineering and Computer Science, Physics, Mechanical Engineering, Materials Science and Engineering, Mathematics, the Engineering Systems Division, and the Harvard-MIT Division of Health Sciences and Technology.

During the past year, approximately 275 graduate students and 50 undergraduates from 10 MIT departments and divisions pursued research within RLE. The research is supported primarily by Department of Defense agencies, the National Institutes of Health (NIH), the National Science Foundation (NSF), the National Aeronautics and Space Administration, and the Department of Energy. In addition, numerous projects are funded through industry and private foundations. RLE research is widely varied and consists of six major interrelated groupings: circuits, systems, signals, and communications; multiscale bioengineering and biophysics; nanoscale science and engineering; photonic materials, devices, and systems; physical sciences; and quantum computation and communication.

Detailed information about RLE research in AY2009 can be found in RLE Progress Report No. 151. The report is available online at http://www.rle.mit.edu/media/media_pr.html. The following is a summary of research highlights from the past year.

Circuits, Systems, Signals, and Communications



Professor Jacob White uses a range of engineering design applications to drive research in simulation and optimization algorithms and software. His group's recent efforts have focused on numerical techniques associated with problems in biotechnology and nanotechnology. Applications include nanophotonic signal processing (in collaboration with professor Steven Johnson), mass-action kinetics modeling of transduction networks in biological cells (in collaboration with professor Bruce Tidor), and fast methods for Casimir force computation (in collaboration with professor Steven Johnson). A highlight from the past year's research

is an algorithm for computing Casimir forces between arbitrarily shaped perfect conductors, which is currently being used by researchers at S.T. Microelectronics to assess the impact of Casimir forces in micromachined devices. Casimir forces can play a role at separation distances less than 100 nanometers, and hence being able to predict such forces can be important in a wide range of nanotechnology applications.

Professor Luca Daniel leads research ranging from the development of a capacitance solver for variation-aware extraction to model-order reduction techniques for linear and nonlinear dynamical systems and the use of field solvers and model-order reduction in modeling the human cardiovascular system. During the past year, his group has developed a general model-order reduction framework that enables any of the existing projection-based reduction techniques to preserve stability in the reduced linear system or even enforce stability, regardless of the matrix structure of the original system. This work was reported at the 2008 Institute of Electrical and Electronics Engineers (IEEE) International Conference on Computer-Aided Design, where it won a best paper award. In other research, Professor Daniel has established a collaboration with Dr. Karim Azer, who leads Merck's cardiovascular system modeling group, with the goal of applying state-of-the-art model-order reduction to studies of the cardiovascular and circulatory systems.

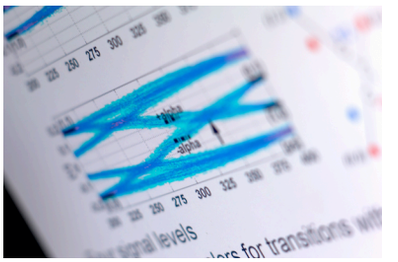
Professor Jae Lim's Advanced Telecommunications and Signal Processing group is developing new video compression methods for use in reducing the bandwidth required for video communications and the storage required for video recording. A particular focus is the development of new transforms for video compression, which have the potential for efficient transmission of 3D television signals.

The research of professor Vivek Goyal and his students spans several areas of signal processing, information theory, and communication theory. Their recent focus has been on problems in information acquisition and representation that exploit sparsity and respect resource constraints such as power limitations. During the past year, his group has obtained some of the strongest and most conclusive analyses of compressed sensing—the combining of data acquisition with data compression that is being applied with a variety of imaging systems such as charge coupled devices and magnetic resonance imaging (MRI). This work has revealed the fundamental roles of signal-to-noise ratio and dynamic range and established the relative merits of various compressed sensing algorithms, thus replacing scattered and incomplete knowledge of performance bounds with exact computations.

Professor Alan Oppenheim's Digital Signal Processing group continues to work on a broad array of problems in the area of signal processing and its applications. A primary focus is on algorithm development in general, with applications serving as motivating contexts. Approaches to new algorithms have come from unconventional directions, such as fractal signals, chaotic behavior in nonlinear systems, quantum mechanics, and biology. A recent example is the relationship between thermodynamic systems and the signal flow graphs that are used to represent them.

The research of professor Vincent Chan and his students addresses a broad range of topics in the general area of networks and communications, with an emphasis on satellite, wireless, and optical systems. The current focus of their effort is the technology and architecture encountered in modern heterogeneous networks. Currently such networks suffer from low throughput, long delays, and an inability to guarantee critical message delivery, among other problems. Addressing these shortcomings requires architectural constructs that range from physical media to upper-layer network protocols. So far, the group has been able to suggest plausible solutions for many problems in heterogeneous networks. In other research, Professor Chan's flow switching network transport mechanism has triggered a follow-on NSF program in which his group will work with Alcatel Lucent, Bell Laboratories, and Cisco on a network test bed to solve interaction problems between the physical medium and the upper-layer network protocols.

Professor Gregory Wornell is interested in algorithms, architectures, communication, and storage in wireless, multimedia, and sensor networks as well as architectures, abstractions, and technology for coherent imaging. During the past year, he has developed rich connections between the techniques used in physical optics and sensor processing communities in electrical engineering and the techniques used in computer vision and computational photography communities in computer science. In other work, he has developed a powerful new underwater acoustic modem technology as part of an effort to substantially upgrade the Navy's underwater communications capability. This new system uses super-Nyquist signaling and rateless coding, whose large bandwidth gains were verified in the large experimental effort associated with this research.



Professor Vladimir Stojanovic's Integrated Systems group focuses on designing methodology, circuits, and system techniques for both traditional and emerging technologies. His group has created a vertical modeling framework for design and performance evaluation of core-to-core and core-to-memory networks based on both equalized copper interconnects and emerging devices such as carbon nanotubes and silicon-photonic interconnects. Professor Stojanovic leads a multidisciplinary silicon photonics team composed of professors Rajeev Ram, Franz Kärtner, Judy Hoyt, Erich Ippen, and Henry Smith. They have designed the first-ever electrophotonic chip in 32-nanometer bulk complementary metal-oxide-semiconductor (CMOS) technology, and the first experimental results indicate that this technology node is capable of producing high-quality photonic devices in the same process as high-performance transistors. This platform for the first time features full electronic link functionality and in situ device testing through wavelength-division multiplexing.

Professor Muriel Médard leads a highly collaborative research group, with research links to the Computer Science and Artificial Intelligence Laboratory and the Laboratory for Information and Decision Systems at MIT, as well as the California Institute of Technology, the University of California at Los Angeles, the University of Illinois at Urbana-Champaign, and the Technical University of Munich—whose central theme is

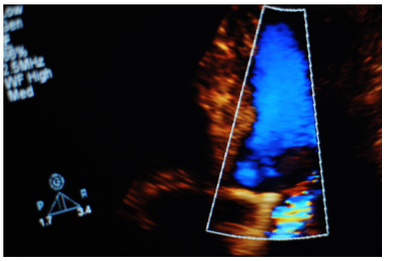
network coding. A focus of this year's research is her work on equivalence in networks, specifically connecting the information flow and routing issues for noise-free bit pipes that appear in network models with the questions of capacity regions for noisy broadcast and multiple access channels that appear in multiterminal information theory. Here separation issues—between network coding and channel coding—have revealed that many network problems are combinatorial rather than statistical. Indeed, the central problem appears to be as follows: given a network of error-free, rate-constrained bit pipes, is a given set of demands satisfiable or not? This question has a simple answer for multicast demand, but the general case is still open and may be computationally hard.

Professor David Staelin is interested in improved methods for remote sensing of global precipitation from current operational meteorological satellites, the analysis of ad hoc wireless communication networks, and studies of spike-timing models for neural computation. A research highlight from the past year is the first continuous mapping of North Pole precipitation within the 80ºN circle for the summer months. This highly fragile environment is exhibiting rapid changes in ice cover and type, and precipitation plays a major role in its evolution. In his neural signal processing effort, Professor Staelin has derived 0.3 bits per synapse as the maximum information storage capacity of a hypothetical neural network architecture that uses spike timing and is subject to neural threshold noise at small percentage levels. These optimum hypothetical subnetworks would only need to resolve four to six time slots within one period of a gamma wave and predict approximately one synapse connecting any two neurons, as observed in nature.

Professor Anantha Chandrakasan has developed a pulsed ultrawideband receiver system-on-chip (SoC) designed to meet the stringent size, weight, and power constraints of the cyborg moth project that professor Joel Voldman leads. His chip, which was mounted on a miniature 1.2-cm by 2.5-cm printed circuit board and attached to the moth's ventral side using a harness, has successfully received packets that were used to control the moth's direction of flight by means of a neural stimulator inserted at the junction of the moth's thorax and abdomen. The SoC was fabricated in 90-nanometer CMOS and provides a 16 Mbps instantaneous data rate with −76 dBm sensitivity at a 10^{-3} bit error rate. It operates in a duty-cycled mode of one packet per millisecond, drawing an overall average system power of 2.5 mW. The design techniques employed in constructing this receiver may have broad applications to short-distance low-power wireless communications such as personal telemetry systems.

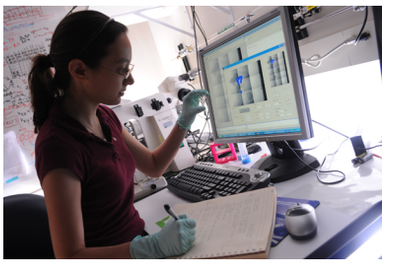
Multiscale Bioengineering and Biophysics

The research of professor Collin Stultz is focused on understanding conformational changes in biomolecules that play important roles in common human diseases. His group uses an interdisciplinary approach that combines computational modeling with



biochemical experiments to make connections between conformational changes in macromolecules and disease progression. His recent computational work has enumerated the low-energy conformational states of both type I and type III collagen, and he has performed experiments to validate the hypotheses that arose from these computational studies. Because collagen degradation has been implicated in the pathogenesis of atherosclerosis, tumor metastasis, and arthritis, Professor Stultz's collagen research may lead to effective therapies for a number of common disorders.

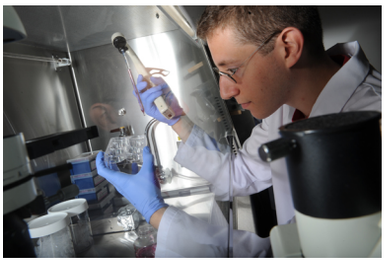
Professor Elfar Adalsteinsson's group is developing methods for MRI in human health and disease. An ongoing trend in MRI is the push to high-field-strength imaging because of the improved signal-to-noise ratio and, thus, better spatial resolution and shorter imaging times it provides. Professor Adalsteinsson works on overcoming the severe signal inhomogeneity problem that plagues such high-field-strength systems. Using the 7T platform at the Health Sciences and Technology Martinos Center at the Massachusetts General Hospital, he has validated the parallel transmit (pTx) radio frequency (RF) system—which is based on earlier research from his group—within the low-power domain and has been extending this pTx work to incorporate limits on RF power deposition, which is a regulated safety parameter. Another highlight from the past year's research is Professor Adalsteinsson's demonstration that quantitative oxygenation consumption parameters can be derived from noninvasive MRI measurements in human subjects. A patent application has been filed on this concept.



Professor Joel Voldman's research interest is the development of microsystems for manipulating cells for fundamental and applied biology. His group's four themes are (1) technologies for image-based cell sorting, (2) novel dielectrophoretic cell separators for cell screening, (3) microtechnology for studying fundamental stem-cell biology, and (4) microsystems for controlled flight of insects. This year he reported dielectrophoretic separations for measuring cell properties that, for the first time, allow many cells' electrical properties to be monitored as their surroundings are changed. This capability is of critical importance in both fundamental biophysics and medical applications. In other work, his group developed a microfluidic device for pairing and fusing cells that will enable studies in nuclear reprogramming, which is currently a hot topic in stem-cell biology.

The work in professor Jongyoon Han's Micro/Nanofluidic BioMEMS group is focused on developing sample-preparation microdevices for various biosensing problems, including immunoassays and enzyme assays, as well as novel methods for fabricating preconcentrator systems. Much of his time during the past year has been spent launching his involvement with the Singapore-MIT Alliance for Research and Technology (SMART) Center. Significant effort has been devoted to laboratory renovation in Singapore as well as staff hiring and establishing collaborations. His

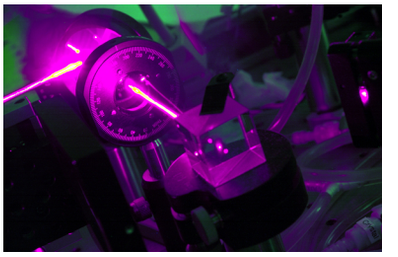
group's work on microfluidic mechanical cell sorting has been extended to a variety of cell types, including malaria-infected red blood cells and human mesenchymal stem cells. Their development of an in vitro cellular kinase activity assay—using biomolecular concentration enhancement—has increased the sensitivity of existing fluorogenic kinase activity assays to the level of one to five cells. Their assay may enable cellular signaling pathways to be studied at the single-cell level, that is, without incurring the unwanted blurring that less sensitive assays suffer because they average over many cells in culture.



Professor Mehmet Fatih Yanik works on the development of high-throughput in vitro and in vivo genetic and chemical screening technologies for neurobiology assays ranging from neuronal regeneration to neurite pathfinding and plasticity. During the past year, his group has used high-throughput on-chip screening to evaluate several compounds that enhance regeneration with a wide variety of cellular targets, such as cytoskeletal components, vesicle trafficking, and protein kinases to improve mechanosensory neuron regeneration following laser axotomy. Ultimately, these small molecules might find applications in therapeutic treatment of central nervous system pathologies such as spinal cord injuries, brain trauma, stroke, and neurodegenerative disorders.

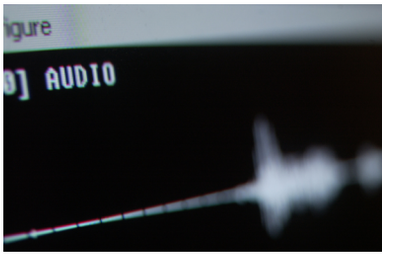
Professor Rahul Sarpeshkar and his students are working on bio-inspired circuits for radio frequencies; on brain-machine interfaces for the treatment of blindness, paralysis, and Parkinson's disease; and on circuit models for the heart. A major research achievement from the past year is the construction of RF cochlea chips that operate from 600 MHz to 8 GHz with 300 mW of power and 70 dB of dynamic range, making them useful as front ends in software, universal, and cognitive radios for a very broadband frequency range. This work has pioneered an important bridge between the fields of hearing science and RF circuit design and has drawn a great deal of media attention. In other research, Professor Sarpeshkar's group has created a CMOS chip that implements an analog electronic circuit model of the heart. It is useful for low-power body sensor networks that employ analysis-by-synthesis techniques to estimate cardiovascular parameters for medical monitoring.

Professor John Wyatt leads the Boston Retinal Implant Project, whose long-term goal is the development of a chronically implantable wireless retinal implant to restore some level of useful vision to patients with outer retinal diseases such as retinitis pigmentosa or macular degeneration. This project has advanced to the point at which the next step is the practical issue of chronic implantation of the wireless prosthesis in the eyes of Yucatan minipigs. After a long series of minor redesigns, his group successfully implanted a first-generation device for 10 months without inducing any serious tissue damage or apparent discomfort to the animal. The device could be turned on and stimulated wirelessly at any time. The group also was able to implant a hermetically sealed second-generation device that can continue to function for the 10 years required for approval by the Food and Drug Administration. It survived well for four months, again functioning wirelessly for the entire time without major evidence of bioincompatibility.



Professor James Fujimoto divides his research efforts between two areas: biomedical optical imaging and diagnostics, and ultrashort-pulse laser technology. In his biomedical imaging work, he continues to pioneer optical coherence tomography (OCT), a field that his group created in 1990. OCT is a medical imaging technology analogous to ultrasound. During the past year, Professor Fujimoto began clinical endoscopic studies in collaboration with Dr. Hiroshi Mashimo of the Veterans Administration Medical Center using new high-speed OCT technology. These ongoing studies involve imaging of the upper and lower gastrointestinal tracts and investigation of treatment response to ablative therapies. In other work, Professor Fujimoto has demonstrated multiphoton microscopy imaging—in collaboration with Dr. David Boas at the Massachusetts General Hospital—using new diode-pumped solid state lasers developed by his group. Multiphoton microscopy is one of the most powerful imaging modalities used in fundamental biomedical research. Professor Fujimoto's new laser sources can substantially reduce the cost of this technology, thus enabling its wider use.

Professor Kenneth Stevens leads a research group whose principal aims are to develop a model of human production and perception of speech, to explain the bases for the units underlying this model in terms of the biomechanical and bioacoustical structure of the system, and to account for individual differences in the functioning of the model for normal and disordered speech. Work during the past year has concentrated on developing a theory that attempts to account for the universal inventory of speech sounds observed in human language. This research has application to the study of children's acquisition of speech, methods of quantifying speech disorders, and training for second-language learning.

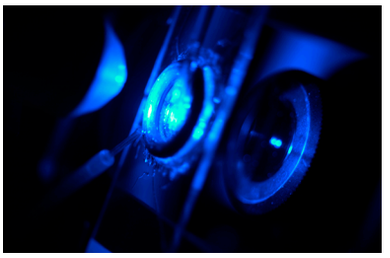


Dr. Joseph Perkell has two research projects under way: Constraints and Strategies in Speech Production and Effects of Hearing Status on Adult Speech Production. During the past year, he has performed a series of experiments that address the perceptually important aspects of speech's spectral structure in time-varying sound sequences. His experiments demonstrate, for the first time, that time-varying aspects of speech movements are programmed very precisely and that the feedforward component of this programming may be modified when temporal aspects of the produced sounds do not match preprogrammed auditory expectations. Detailed investigations of speech timing may be particularly useful in understanding some of the neural mechanisms underlying stuttering, a commonly occurring speech disorder that is characterized largely by a breakdown in the orderly timing of speech movements.

Professor Louis Braida's research has as its long-term goal the development of improved hearing aids and cochlear implants. Specific goals for his work include evaluating the effects of the style of speech articulation on speech reception by the hearing impaired, developing accurate analytic models to predict the effects of speech-signal alterations

on intelligibility, and developing signal-processing techniques that will increase the effectiveness of hearing aids. A continuing focus of his work has been to understand the role of audibility in speech reception by listeners with hearing impairments.

Dr. Bertrand Delgutte is a member of the Eaton-Peabody Laboratory of Auditory Physiology. His research addresses the neural mechanisms of listening in everyday environments composed of noise and reverberation. One focus of his work is the neural basis for speech reception and sound localization in reverberant environments. Another focus is neural sensitivity to interaural time differences—the most important sound localization cue—in animal models of bilateral cochlear implants. Results from the bilateral implant experiments indicate that neural sensitivity to interaural time differences in animal models of cochlear implants is better with irregular pulse trains as opposed to periodic pulse trains. Because current sound processors for cochlear implants use periodic pulse trains, this finding offers hope for designing new processors that would provide better sound localization and speech reception in noise.



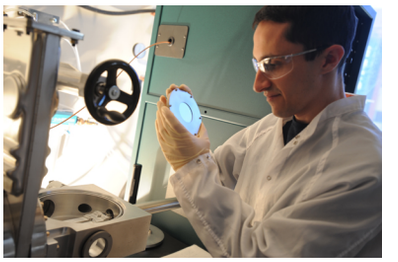
Professor Dennis Freeman has made further advances in his investigations of the way the inner ear functions. Previously he had discovered that the tectorial membrane, a gelatinous structure in the inner ear, supports longitudinally propagating traveling waves. In recent work using mouse models, he found that the spatial extent of tectorial membrane traveling waves is greatly diminished by the Tectb−/− mutation. This result provides an explanation for the otherwise difficult-to-understand properties of hearing in these animals, which show decreased sensitivity accompanied by increased frequency selectivity. His research could have application to the clinical diagnosis and treatment of hearing disorders.

Dr. Mandayam Srinivasan leads the Laboratory for Human and Machine Haptics. Whereas he has long studied the mechanics and mechanisms of tactile sensation in humans and primates, during the past year he has initiated the study of touch in the nematode *C. elegans*. This model organism will afford him the opportunity of studying the role of genetics in touch sensations, as well as the protein machinery behind tactile sensation. So far, the observed mechanical response of the nematode—measured using a modified atomic force microscope—has been different from what would be expected from Hertz contact theory. Work is presently under way to develop new biomechanics models to better explain the observed responses.

Nanoscale Science and Engineering

Professor Henry Smith codirects the NanoStructures Laboratory with professor Karl Berggren. Its dual mission is the development of advanced nanofabrication technology and the application of that technology to research in optical, electronic, and magnetic devices. A highlight from this year's effort in Professor Smith's group is Dr. Rajesh Menon's invention of absorbance modulation lithography. By using optical nonlinear behavior in photochromic chemistry with illumination at 325- and 633-nanometer wavelengths, this technique demonstrated 35-nanometer photolithographic resolution (i.e., approximately one tenth the optical wavelength). This result stands in stark contrast

to traditional theory, which dictates that the resolution cannot be better than half the wavelength. Hence, it promises a new form of optical lithography that might yield resolutions as fine as one fortieth of the wavelength.



Research in professor Karl Berggren's Quantum Nanostructures and Nanofabrication group has continued on nanometer-length-scale single-photon detectors and new techniques for combining block-copolymer self-assembly with electron-beam lithography. Photon detector work during the past year has focused on developing a system in a closed-cycle cryocooler. The detector was fiber coupled, yielding a plug-and-play system that required no extra cryogens. The new detector system, which set a record of 24.4% system detection efficiency, will be important to applications ranging from quantum communications to interplanetary optical communications. Professor Berggren's work on block copolymers, in collaboration with professors Caroline Ross and Edwin Thomas (both from the Department of Materials Science and Engineering), uses electron-beam lithography to pattern a structure of 10-nanometer-diameter, 35-nanometer-tall posts in a hexagonal grid that act as pinning sites for copolymer self-assembly. The order and orientation of the self-assembled block copolymers were shown to be in agreement with a free-energy theoretical model. The results of this work will have applications in the data-storage industry, as molds or etch masks for bit-patterned media.

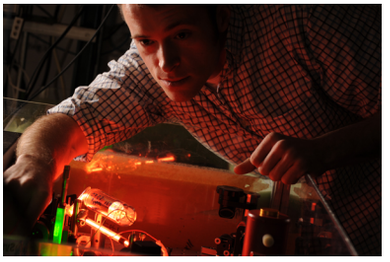
Professor Jing Kong is interested in the fabrication and applications of single-walled carbon nanotubes, graphene synthesis and transfer technology, and nanowire assembly and its applications. Her recent work includes development of a carbon nanotube synthesis setup to deposit single-walled nanotubes directly on temperature-sensitive substrates. In addition to enabling fundamental Raman characterization studies, this synthesis setup will be useful for producing nanotube transparent electrodes. In her graphene synthesis research, Professor Kong is now able to obtain up to 87% of the film area having only one or two layers of graphene. With greater control of graphene film uniformity, this material will become a promising candidate for high-frequency amplifiers and other integrated-circuit applications.

Photonic Materials, Devices, and Systems

Professor Leslie Kolodziejski and Dr. Gale Petrich lead the Integrated Photonic Materials and Devices group, whose research centers on fabricating photonic and optoelectronic devices, including saturable Bragg-reflector mirrors (SBRs), ultrabroadband modulators, and photonic integrated circuits for demonstration of ultrafast optical logic. During the past year, their group's collaboration with professors Erich Ippen, Franz Kärtner, and James Fujimoto has resulted in the design, fabrication, testing, and deployment of SBRs for a variety of novel short-pulse laser systems. These femtosecond-pulse lasers, which cover wavelengths ranging from 800 to 1,600 nanometers, depend on the unique capabilities provided by 100-nanometer-bandwidth

SBRs that were designed, fabricated, and tested in this collaboration. The group's SBRs have also stimulated considerable interest from industry, including both Q-Peak Inc. and ThorLabs.

Professor Erich Ippen has continued his work on the advancement of femtosecond optical techniques and their application to studies of ultrafast phenomena. He leads a Defense Advanced Research Projects Agency program on optical arbitrary waveform generation using stabilized femtosecond optical combs. A highlight from the past year's research is the extension of femtosecond fiber-laser technology to high repetition rates by means of soliton modelocking in short fiber lasers and integrated waveguide devices, work that was done in collaboration with professors Kärtner and Kolodziejski. In other work, done in collaboration with researchers at IBM, Professor Ippen has designed and demonstrated novel low-power and ultrafast silicon switches. The present devices employ optical excitation; electronic control is being pursued. High-performance silicon microphotonics will enable a variety of applications in optical communications, ranging from optical fiber networks to multiprocessor interconnect in computers.



Professor Franz Kärtner is working on high-repetition-rate femtosecond lasers and optical frequency combs for applications in photonic analog-to-digital conversion, optical clocks, calibration of astrophysical spectrographs (in collaboration with the Harvard-Smithsonian Center for Astrophysics), and optical arbitrary waveform generation. He is also interested in nanophotonics with high-index-contrast silicon waveguides, parametric chirped-pulse amplification to generate high-energy carrier-envelope phase-controlled pulses, and attosecond science. During the past year, he has demonstrated the first integrated femtosecond waveguide laser with the low timing jitter needed for photonic analog-to-digital conversion. Also, together with professor Henry Smith and researchers at MIT Lincoln Laboratory, he has demonstrated a silicon-based electro-optic modulator with 26-GHz bandwidth and a 20-channel filter bank. Finally, he has constructed and operated a compact methane-stabilized frequency comb and optical clock reaching a stability of 3×10^{-14} at 20 seconds.

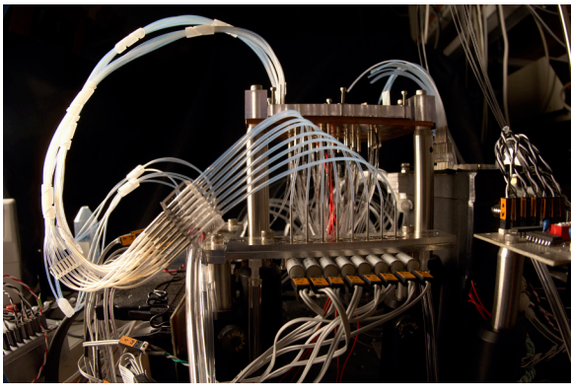
Professor Steven Johnson's research agenda comprises three general problem categories in nanophotonics: What new effects and devices can one achieve in such structures? How does one design devices given so many degrees of freedom? and What higher-level understanding can one develop for such complex systems? Highlights from his research during the past year are the first precise theoretical description of stable suspension using quantum Casimir forces for electrically neutral, fluid-separated objects; a new class of highly efficient devices for nonlinear frequency conversion using optical microcavities; and new techniques for robust optimization in large-scale computation applied to design with manufacturing uncertainties. His robust-optimization work will be applicable to a wide range of design problems for which computers are increasingly being used to search the available parameter space to avoid designs that fail in the presence of manufacturing errors. His Casimir force research—done in collaboration with professor Jacob White—will become increasingly important as micromechanical devices enter new regimes of miniaturization.

Professor Marc Baldo is interested in electronic and optical processes in molecules, especially as applied to organic solar cells and light-emitting devices. In the past year he has made major progress in his work on solar concentrators by improving the performance of his device in the infrared. This was accomplished through use of neodymium-doped glasses similar to those used in high-power lasers. Professor Baldo is the director of the Center for Excitonics, a newly funded Department of Energy Frontier Research Center. The overarching theme of this new center is to supersede traditional electronics with devices that use excitons to mediate the flow of energy. Whereas the former rely on expensive and energy-intensive fabrication processes, the latter are far more suitable for the large-scale production that would be needed for the production of sufficient solar cells to have a significant impact on the world energy supply.

Professor Vladimir Bulovic's laboratory is addressing a wide variety of topics related to hybrid organic/inorganic optical and electronic devices. Among his group's research achievements from the past year is the demonstration of an optical feedback technique to counter pixel aging in organic light-emitting devices (OLEDs) that maintained OLED video brightness to within two percent accuracy for more than 25,000 hours of continuous operation. This work has redefined the commonly misunderstood metric for OLED lifetime and has shown that OLED technology cannot be used for most video display applications unless optical feedback is employed. In other work, he has developed a novel two-terminal, lateral organic bilayer photoconductor that exhibits photon-to-electron conversion gain. This structure, for the first time, separates the photosensitive and semiconductive portions of the device so that each can be optimized independently. The exposed top layer enables interaction with chemical analytes, motivating the use of this structure as a chemical sensor that transduces chemical signals into amplified changes in the electrical response.

Professor Qing Hu's research is devoted to developing terahertz (THz) quantum cascade lasers and electronics; real-time THz (T-ray) imaging using quantum-cascade lasers and focal-plane cameras; and high-power, mid-infrared quantum cascade lasers with high wall-plug efficiency. His THz quantum cascade lasers have achieved world-record performance in many respects: the highest operating temperature in the pulsed mode (186 K without and 225 K with an applied magnetic field), the highest operating temperature in continuous-wave mode (117 K), the highest power levels (250 mW), and the longest wavelength (190 microns). He has also performed T-ray imaging at a video rate of approximately 20 frames per second using one of his sources. More generally, these THz sources will be of great importance in opening up this spectral region for sensing, imaging, and high-bandwidth communications.

Professor Rajeev Ram's Physical Optics and Electronics group has three primary themes: the demonstration of photonic devices in state-of-the-art CMOS integrated circuit processes, the demonstration and analysis of solar thermoelectric power generation as an alternative to photovoltaic's, and the development of precommercial prototypes of microscale automated cell culture systems. Key achievements from the



past year include the first demonstration of waveguide devices in a deep-submicron process and in a zero-change foundry process, successful field trials of solar thermoelectric generators in rural China and Nepal, and an award from the Massachusetts Technology Transfer Center to commercialize his microbioreactor technology. Professor Ram is also the director of the Center for Integrated Photonic Systems and in charge of the Integrated Photonics Initiative.

Professor Peter Hagelstein works on a variety of applied problems relating to unconventional approaches to energy generation. During the past year, he has concentrated on documenting the key theoretical advances he has made in this area. These advances include a new version of Fleischmann-Pons models that he hopes to compare with emerging data from experiments at SRI, initial development of a new computational transport model for thermal diodes, and work with MTPV on a new nanogap thermal-to-electrical converter. Both the thermal diode and thermal-to-electrical converter may lead to new commercially viable technologies. The work on excess heat in Fleischmann-Pons experiments is expected to contribute to development of more reliable excess heat-producing configurations.

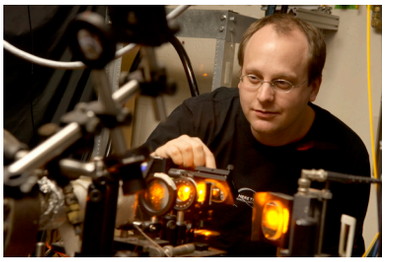
Professors John Joannopoulos and Marin Soljacic work on the theory of electromagnetic phenomena, especially those involving nanophotonics, nonlinear optics, and wireless power transfer. A key result from their past year's research is the theoretical demonstration that photonic crystal cavities can dramatically enhance THz generation starting from optical-frequency fields. This result could have considerable significance, as THz radiation has many applications in chemical sensing, biology, and security. Professor Joannopoulos is director of the Institute for Soldier Nanotechnologies.

Professor Yoel Fink's research interests are the theory, design, process development, and characterization of fibers with engineered electronic, photonic, and phononic properties that follow from their elaborate structure and multiscale features. A major accomplishment from his past year's research is a novel eight-device fiber that can measure the relative intensity of light at two different wavelengths. When woven into a square-foot grid, these fibers—which have nanoscale features—permit an object to be imaged without use of a lens. This work is illustrative of the vast new opportunities that are afforded for integrating electronic, optical, and acoustic functionalities into polymeric fiber and textile yarns. In short, Professor Fink's research has introduced a new paradigm for fabrication that spans length scales from tens of nanometers to kilometers.

Physical Sciences

Professor Wolfgang Ketterle's research concentrates on the properties of bosonic and fermionic quantum gases, the use of ultracold atoms to realize new forms of matter with strong interactions and strong correlations, and the study of many-body

physics using quantum degenerate gases. During the past year, his work led to a major new result on the superfluidity of ultracold fermions. A central parameter in the description of superfluids is the gap, which is proportional to the superfluid transition temperature and the binding energy of the paired fermions. Professor Ketterle, for the first time, was able to experimentally determine the gap using radio-frequency spectroscopy. The coherent-atom sources that he studies may replace conventional atomic beams in demanding applications such as atom interferometry, precision measurements, atomic clocks, and matter-wave microscopy. Professor Ketterle directs the MIT-Harvard Center for Ultracold Atoms.



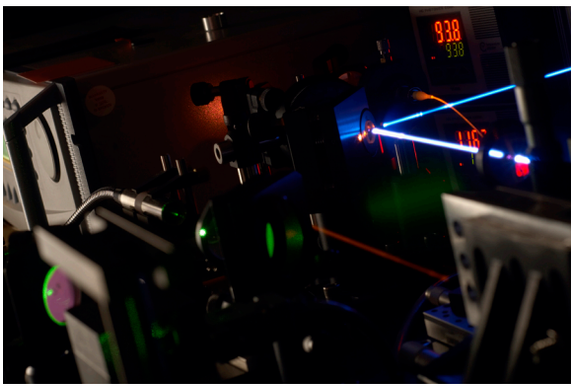
Professor Martin Zwierlein is an experimentalist who is interested in the properties of ultracold gases of atoms and molecules as a universal test bed for condensed matter and nuclear theory. He has two laboratories. One is used to study unequal mixtures of spin-up and spin-down fermions with tunable interactions. The second, which has just come on line, will study mixtures of different fermionic atoms. Here the initial focus will be on certain universal impurity problems relevant to condensed-matter physics, especially colossal magneto-resistance. Professor Zwierlein's experiments will constrain and validate many-body theories of strongly interacting matter in an ideal environment. His work may also lead to the design of new high-temperature superconductors.

Professor Vladan Vuletic is interested in quantum optics and quantum information processing using laser-cooled atomic ensembles. In recent work, his group has demonstrated a novel, dynamic method to create entangled states of the atoms in an atomic clock. This method significantly improves the atomic clock's signal-to-noise ratio, reducing the required integration time for a given clock precision by a factor of four, which is the largest improvement demonstrated in any such system. It also provides a direct path to achieving even higher signal-to-noise ratios in the near future. Other research accomplishments from the past year include demonstration of fast switching of light at the level of a few hundred photons per pulse and a quantum memory for storing the polarization state of single photons.

Professor David Pritchard has developed a new pedagogy to help students become more expert problem solvers. Called Modeling Applied to Problem Solving (MAPS), this approach uses models to present and hierarchically organize core syllabus content and apply it to problem solving. Unlike typical modeling pedagogies, MAPS does not ask the students to construct and validate their own models. Instead, they are asked to classify problems under the appropriate core model or models by selecting a system to consider and describing the interactions that are relevant to that system. Professor Pritchard's MAPS approach allows modeling physics to be integrated into—as opposed to replacing—a typical introductory college mechanics course. He is actively promoting MAPS pedagogy at local and national meetings of physics educators.

Quantum Computation and Communication

Professor Seth Lloyd's work focuses on problems of information processing in both the quantum-mechanical and classic regimes. He is the director of the W. M. Keck Foundation Center for Extreme Quantum Information Theory (xQIT) and leads a group that has investigated the fundamental limits on the capacity of communication channels, derived bounds on the sensitivity of measurement devices, and constructed novel designs for quantum computers and quantum memories. Together with professor Jeffrey Shapiro, Dr. Vittorio Giovannetti (Scuola Normale Superiore), and Dr. Lorenzo Maccone (University of Pavia), he has recently proved an important outstanding conjecture in quantum communication, namely the minimum output entropy conjecture for bosonic channels. The proof of this conjecture immediately establishes the ultimate classical information capacity of the most important quantum-optical communication channels and will be of use in designing truly optimum optical communication systems. In other work, with professor Alan Aspuru-Guznik (Harvard University), he has developed a theory of photosynthetic transport in terms of quantum walks. This theory explains the anomalous efficiency of energy transport in photosynthesis and may lead to photocollector designs with improved efficiencies.



Professor Jeffrey Shapiro and Dr. Ngai Chuen (Franco) Wong lead the Optical and Quantum Communications group, which has been working on the generation of entangled photons and their applications in quantum communications and quantum cryptography. Experimental work during the past year demonstrated the factor-of-two resolution advantage and the dispersion-cancellation property of phase-conjugate optical coherence tomography, a new OCT imaging modality suggested by the group's previous theoretical research. Another experimental effort has led to a waveguide parametric downconversion source of photon pairs with a production rate of 2×10^7 pairs per second per milliwatt of pump power in a 1-nanometer bandwidth. This source yielded a Hong-Ou-Mandel dip visibility of 98.2%, after subtraction of accidentals, which is the highest reported value for a waveguide-based photon-pair source. The group's theoretical work has determined the signal-to-noise ratio behavior of classical and quantum ghost imaging configurations, namely imagers that rely on correlations between signal and reference beams in which the signal beam interacts with the object but is observed on a detector without spatial resolution whereas the reference beam does not interact with the object but is detected at high spatial resolution. It was also shown, theoretically, that a single-beam (no reference) configuration can be employed for ghost imaging, and this result was experimentally confirmed by a group at the Weizmann Institute.

The research in professor Isaac Chuang's group is directed toward understanding and demonstrating the harnessing of resources provided by quantum physics for novel applications in information technology. The most exciting experimental result from his

laboratory this year has been the development of a microfabricated chip for trapping single atomic ions, which are each used as quantum bits in a quantum processor. These chips are operated at cryogenic temperature and provide quantum bits that live in quantum states of motion for times that are three orders of magnitude longer than what is achieved in the best comparable traps elsewhere. In his theoretical work, Professor Chuang has discovered, for the first time, a recipe for a material that could exist in principle and would have a configuration of quantum bits that would allow error-free quantum computation when operated at zero temperature. Such a recipe had long been sought in the quantum information community. Professor Chuang is the director of the NSF Integrative Graduate Education and Research Traineeship (IGERT) program titled Interdisciplinary Quantum Information Science and Engineering.

Appointments, Awards, and Events

The following appointments and awards were made in AY2009.

Professor Isaac L. Chuang was promoted to professor of electrical engineering and physics.

Professors Marc A. Baldo, Karl K. Berggren, Jongyoon Han, Joel Voldman, and Lizhong Zheng were granted tenure.

Professor Jing Kong was promoted to associate professor of electrical engineering.

Professor Vladimir M. Stojanovic was promoted to associate professor of electrical engineering and computer science.

Professor Marc A. Baldo was appointed director of the Center for Excitonics.

Professor John D. Joannopoulos was elected to the National Academy of Sciences.

Professor Marin Soljacic received a 2008 MacArthur Fellowship.

Professor Anantha P. Chandrakasan received the Semiconductor Industry Association University Researcher Award.

Professor James G. Fujimoto received the 2009 Hounsfield Medal from the Imaging Sciences Center of Imperial College.

Professor Wolfgang Ketterle received a Humboldt Research Award.

Professors Jing Kong and Mehmet Fatih Yanik received NSF CAREER Awards.

Professor Mehmet Fatih Yanik received an NIH EUREKA Award.

Professor Franz X. Kärtner was elected an IEEE Fellow.

Professor Henry I. Smith was elected a fellow of the Optical Society of America.

Professor Jeffrey H. Shapiro received the 2008 Quantum Communication Award for Theoretical Research from Tamagawa University.

Professor Henry I. Smith received a 2008 Nano 50 Award.

Professor Joel Voldman received the Young Innovator Award from the American Chemical Society journal *Analytical Chemistry*.

Professors Luca Daniel and Vladimir M. Stojanovic received best paper awards at the 2008 IEEE International Conference on Computer-Aided Design.

Professor Muriel Médard was corecipient of the IEEE Communications Society 2009 William R. Bennett Prize in the Field of Communications Networking.

Professor Muriel Médard was corecipient of the IEEE Communications Society and IEEE Information Theory Society 2009 Joint Paper Award.

Professor Marc Baldo's work on solar concentrators was named one of *Discover* magazine's Top 100 stories of 2008.

Professor Paul B. Corkum presented the Hermann Anton Haus Lecture.

Professor Vladimir Bulovic was named a Margaret MacVicar Fellow.

Professor Vladimir Bulovic received the 2009 Bose Award for Excellence in Teaching.

Professor Leslie Kolodziejski received the Capers and Marion McDonald Award for Excellence in Mentoring and Advising.

Professor Elfar Adalsteinsson received the 2009 Ruth and Joel Spira Award for Excellence in Teaching.

Professors Jongyoon Han and Joel Voldman received the 2009 Louis D. Smullin Award for Outstanding Teaching.

Professor Jing Kong received the 2009 Saltzer Award for outstanding recitation teaching.

Professor Rajeev J. Ram received a Burgess and Libby Jamieson Award honoring great teaching over a long period of time.

Professors Luca Daniel and Jing Kong received 2008 Jonathan Allen Junior Faculty Awards.

Theodore Moallem and Christopher Rohde received 2009 Helen Carr Peake Research Prizes.

Hansen Bow was awarded the Helen Carr Peake Research Assistantship for 2009–2010.

Krista Van Guilder received a 2008 American Graphic Design Award.

Nan Lin was promoted to senior fiscal officer for pre-award administration.

Susanne J. Patterson was appointed fiscal officer.

Albert T. McGurl received a 2009 MIT Infinite Mile Award.

Affirmative Action

RLE has worked and will continue working to increase the number of women and minorities in career positions in the laboratory, in the context of the limited pool of qualified technical applicants and the unique qualifications of RLE's sponsored research staff. Specific measures will include maintaining our high standards for recruitment procedures, among them sending job postings to minority colleges and organizations, working closely with the RLE faculty/staff supervisor at the beginning of each search to identify ways of recruiting minority and women candidates for the new position,

and being committed to finding new techniques to identify women and minority candidates more effectively. During the past year, RLE has promoted one woman on its headquarters staff and appointed another woman to the headquarters staff.

Jeffrey H. Shapiro
Director
Julius A. Stratton Professor of Electrical Engineering

More information about the Research Laboratory of Electronics can be found at http://www.rle.mit.edu/.