Laboratory for Information and Decision Systems

The Laboratory for Information and Decision Systems (LIDS) is an interdepartmental laboratory staffed by faculty, research scientists, and graduate students from several departments and centers across MIT. LIDS provides an intellectually cohesive and collaborative environment that fosters high-quality, forward-looking research and instills in our students the disciplinary depth and interdisciplinary understanding required of research and engineering leaders of today and tomorrow.

Participants and Collaborations

The faculty members within LIDS are principally drawn from the Department of Electrical Engineering and Computer Science (EECS) and the Department of Aeronautics and Astronautics (AeroAstro). However, LIDS has long been interdisciplinary, and recent research foci and the pervasiveness of the analytical methodologies advanced by LIDS researchers have broadened our collaborative scope. Some of the many entities at MIT with which LIDS has a strong relationship include the Computer Science and Artificial Intelligence Laboratory, the Research Laboratory of Electronics (RLE), the Operations Research Center (ORC), the Department of Brain and Cognitive Sciences (BCS), the Department of Civil and Environmental Engineering (CEE), the Department of Mathematics, the Department of Mechanical Engineering, the Department of Economics, and the Sloan School of Management.

LIDS is also a key component of the Institute for Data, Systems, and Society (IDSS), which advances disciplinary methodologies in statistics, data science, and information and decision systems and nurtures cross-cutting connections, especially with the social sciences, to address complex societal challenges. LIDS faculty play a pivotal role in defining the IDSS intellectual agenda—leading efforts in statistics and flagship projects (e.g., in finance, autonomy, and smart cities), designing new academic programs (such as those in statistics and social and engineering systems), and continuing to be heavily involved in the search for new faculty in the fields of networks and statistics. Of particular note this year, LIDS faculty played a central role in launching the IDSS MicroMasters Statistics and Data Science program.

LIDS researchers continue to have great success in obtaining funding for our broad and deep research agenda, and we continue to develop relationships with industrial organizations and national laboratories including Draper Laboratory, Lincoln Laboratory, BBN technologies, the Eaton Corporation, JD.Com, Moody's Investors Service Inc., and Accenture. Also, thanks to a rich history of research excellence and leadership, LIDS remains a magnet for the very best, attracting not only outstanding students but a continuous stream of world-leading researchers as visitors and collaborators.

LIDS has also been strengthened significantly this academic year with the welcoming of several new faculty and researchers, especially in the areas of data science and machine learning. These additions include Professor Suvrit Sra (EECS and IDSS), with expertise in optimization for machine learning; Professor Sasha Rakhlin (BCS and IDSS), with expertise in online learning; Professor Luca Carlone (AeroAstro), with expertise in perception for autonomous systems; and Marija Ilic (newly appointed as a LIDS senior research scientist), a leading researcher on energy systems.

Additionally, the lab redefined the role of LIDS affiliate members this year, fostering stronger ties with a number of MIT faculty who, although not LIDS principal investigators (PIs), are intellectually aligned with the lab's research agenda and involved in substantial interactions. The current affiliate members are Professors Saurabh Amin (CEE), Tamara Broderick (EECS), David Gamarnik (Sloan), Song Han (EECS), Stefanie Jegelka (EECS), Youssef Marzouk (AeroAstro), and Elchanan Mossel (Mathematics).

The strong core of existing LIDS PIs, together with the extended community of affiliate members, has transformed LIDS into a preeminent entity—both within MIT and more broadly in the academic world—in the fields of data science and foundations of machine learning. At the same time, traditional LIDS core areas (communications, information theory, networks, optimization, control, and autonomy) remain active and strong.

Intellectual Vision

The mission of LIDS is to develop and apply rigorous approaches and tools for modeling, analysis, design, and optimization of physical or artificial systems that process information and rely on information for decision making. Research in LIDS encompasses the development of new analytical methodologies as well as the adaptation and application of advanced methods to specific contexts and application domains.

Many of the important recent technological advances involve systems that collect, exchange, and process data and information. Information is then exploited to make decisions, including statistical decisions, resource allocation decisions, and real-time control decisions. This schema captures much of what is happening in an impressive range of fields such as robotics, autonomous systems, intelligent systems, machine learning, life science informatics, computer networks, societal infrastructures, electric power systems, and more. Advances in all of these domains are made in several labs and departments, and domain expertise is typically critical. At the same time, the "information to decisions" viewpoint rests on an intellectual core and on fundamental methodologies that can be applied across disciplines and domains. The objective of LIDS is to serve as a focal point for this intellectual core while advancing work in selected application domains that—in a virtuous cycle—also inspire further methodological research.

To achieve these aims, LIDS research is underpinned by:

- A set of core mathematical disciplines, including probability and statistics, dynamical systems, and optimization and decision theory
- A set of core engineering disciplines, including inference, statistical data processing, data science, and machine learning; transmission of information; networks; and systems and control
- A set of broad challenges in traditional and emerging applications of critical societal importance

The simultaneous efforts along each of these dimensions within the same lab lead to strong synergies: work in the mathematical disciplines leads to new methodologies that advance core engineering disciplines and interdisciplinary applied investigations; conversely, work on new interdisciplinary challenges provides the inspiration and direction for fundamental disciplinary research as well as the charting of emerging new disciplines.

Research Areas

The lab's multiple research strands are usually cross cutting and cannot be neatly organized into categories. Nevertheless, they can be broadly classified in terms of the following core areas:

Statistical inference and machine learning: this area deals with complex systems, phenomena, and data that are subject to uncertainty and statistical variability. It also includes the creation of large-scale data-processing software systems. Research ranges from the development of basic theory, methodologies, algorithms, and computational infrastructures to adaptations of this work for challenging applications in a broad array of fields. Typical applications involve causal inference in experimental design, social data processing, and e-commerce, as well as image processing, computer vision, and automation of data engineering. Other current topics include reinforcement learning and online optimization, recommendation systems, graphical models, large-scale software systems for data engineering, medical image processing, causal inference in genetics, and high-dimensional statistics.

Optimization: the aim of this area is to develop analytical and computational methods for solving optimization problems in engineering, data science, and operations research, with applications in communication networks, control theory, power systems, machine learning, and computer-aided manufacturing. In addition to linear, nonlinear, dynamic, convex, and network programming, research focuses on methods that exploit the algebraic structure of large-scale problems and simulation-based methods.

Systems theory, control, and autonomy: this area deals with all aspects of system identification, inference, estimation, control, and learning for feedback systems. Theoretical research includes quantification of fundamental capabilities and limitations of feedback systems, development of practical methods and algorithms for decision making under uncertainty, robot sensing and perception, and inference and control over networks, as well as architecting and coordinating autonomy-enabled infrastructures for transportation, energy, and beyond.

Networks: this area includes communications, information theory, and networking, with applications to wireless systems, optical networks, and data centers. Research in this area includes the development of fundamental limits on communications systems, design of optimal resource allocation schemes for wireless networks, and design of optimal architectures and control algorithms for data centers and cloud networks. Additional recent directions include analyses of social networks and of agent interactions in networked systems, with applications ranging from the analysis of data generated by large-scale social networks to the study of dynamics and risk in large, interconnected financial, transportation, and power systems.

Moreover, the availability of increasingly capable sensing, communication, and computation enables the collection and transfer of large amounts of data pertaining to complex and heterogeneous interconnected systems. This opens up many new avenues for methodological research in all of the above areas, with some ubiquitous themes such as data fusion, distributed learning and decision making, and issues of scalability, robustness, and performance limits.

Particular areas of significant recent activity are as follows:

- Biological systems and biomedical data analysis
- High-performance unmanned autonomous systems
- Energy systems analysis, economics, and design
- Human-level perception for robotics platforms
- Machine learning for recommendation systems and social media
- Network scheduling and routing
- High-dimensional inference in graphical models
- Networking and information transmission in the context of the Internet of Things (IoT)
- Social network analysis and characterization
- Network navigation and localization
- Transportation network analysis, control, and design
- Ultra-wideband and other emerging communications technologies

Furthermore, the recognition that research within traditional boundaries in information and decision sciences is not adequate to address many of the emerging societal challenges has motivated LIDS to branch out to areas at the intersection of several disciplines. As a result, LIDS is now engaged in several research thrusts that cut across disciplinary boundaries and involve considerable interaction and collaboration with colleagues in other MIT units and in other disciplines:

- Foundations of network science, including network dynamics, control, and efficient algorithms
- Foundational research in game theory and mechanism design involving the study of new equilibrium notions and dynamics in games, as well as the design of efficiently computable incentive methods for large-scale networked, dynamic environments
- New frameworks for modeling and understanding systemic risk
- Fundamental issues in cyber-physical systems, including architectural design, security and privacy, cross-layer algorithms, and tools for analysis, verification, and performance guarantees

- Development of scalable and efficient inference algorithms for problems involving "big data," including basic research on graphical models
- Development of causal inference methods for gene regulation and early disease diagnostics

Research Highlights

Professor Sertac Karaman, in collaboration with Professor Vivienne Sze of RLE, developed the first complete visual-inertial state estimation chip to enable ultra-low-power applications such as insect-sized flapping-wing robotic vehicles.

Professor Eytan Modiano and his group developed new network scheduling algorithms in support of low-latency IoT applications. Their work resulted in best paper awards at two leading conferences in the networking field.

Professor Caroline Uhler and her collaborators developed a method to detect subtle changes in nuclear morphometrics by combining fluorescence imaging and deep learning. This new method enables discrimination between normal and human breast cancer cell lines as well as normal and cancer cells with high accuracy.

Professor Ali Jadbabaie led a multi-investigator project sponsored by the Defense Advanced Research Projects Agency (DARPA) on the fundamental limits of machine learning. The project brought together experts in statistics, machine learning, optimization, algorithms, and applications to develop fundamental limits and scalable methods for large-scale machine learning problems.

Professors Phillippe Rigollet and Devavrat Shah were co-PIs on a multi-year National Science Foundation (NSF) project designed to foster breakthrough discoveries in data science. In the first phase of the project, Rigollet, Shah, and their collaborators founded the MIT Institute for Foundations of Data Science (MIFODS), an interdisciplinary effort to develop the theoretical foundations of data science through integrated research and training activities. Investigators on the project also include four other LIDS faculty and four LIDS affiliate members.

In addition, LIDS faculty members play leadership roles in major new initiatives with applications of critical societal importance, including projects on transportation systems (e.g., the Future Urban Mobility initiative of the Singapore-MIT Alliance for Research and Technology [SMART]), energy systems (e.g., programs in collaboration with the MIT Energy Initiative [MITEI]), and social, economic, and financial networks in close collaboration with Economics and Sloan.

Faculty Activities

The research activities described in the sections to follow are organized in terms of individual faculty members. Nevertheless, many of the activities not only cut across the disciplines, applications, and emerging areas mentioned above but are also collaborative with others within LIDS and elsewhere at MIT.

Dimitri Bertsekas

Professor Bertsekas (McAfee Professor of Electrical Engineering) performs research on problems of sequential decision making under uncertainty, which are pervasive in communication networks, manufacturing systems, logistics, and control of nonlinear dynamical systems. In theory, such problems can be addressed with dynamic programming techniques. In practice, only problems with a moderately sized state space can be handled. This research effort deals with the application of neural networks and other approximation and interpolation methodologies to overcome the curse of dimensionality of real-world stochastic control problems. Recent efforts have focused on the analysis of properties of value and policy iteration methods and their applications in deterministic optimal control. In addition, extensions of the fundamental concept of regular policies in abstract dynamic programming were developed as a follow-up to a research monograph on the subject published in 2013. The second edition of this monograph, published in February 2018, incorporates Professor Bertsekas's latest research.

Professor Bertsekas is also interested in deterministic optimization problems and the role of convexity in solving them, possibly through the use of duality. In recent work, he has been able to establish a connection between the proximal algorithm, which is central in convex optimization, and temporal difference methods, which are prominent in approximate dynamic programming. This continuing work may lead to fruitful cross fertilization between the two fields.

Robert C. Berwick

Professor Berwick's research during the past year included the first systematic evaluation of the so-called "deep learning" natural language processing systems. In particular, Berwick and his students evaluated the accuracy of the commercial Google natural language processor for the first time using all of the training data employed by the Google system for its deep learning. Contrary to what has often been claimed, it was found that accuracy in recovering the critical meaning structure runs at only 50% to 60% rather than 90% or more. The reason seems to be that these models have discarded much of what we have learned about the nature of human language structure from the past seven decades of research. These findings suggest that this knowledge should be reincorporated into existing commercial parsers. They also suggest that the representation format used by the current systems is inadequate to express human knowledge of language. For example, in the sentence "John is hard to convince people to like," it is difficult to convince people to like John. Yet the existing, "best" analyzers get this completely wrong. Conversely, it is easy to recover this meaning from systems built on linguistic knowledge that were developed at MIT over 25 years ago. Thus, this topic deserves further consideration.

In a second thread that parallels this research, Professor Berwick's group systematically analyzed the abilities of so-called "long short-term memory" (LSTM) neural networks to actually acquire some of the knowledge of human language structure even young children possess, particularly hierarchical structure. In this effort, the group sought to determine what sorts of generalizations LSTM systems actually acquire—do they acquire explicit or implicit rule systems that represent hierarchical relations? Again, in contrast to much recent published work, they found that such systems memorize correlational patterns in training data but do not, in general, infer rules. For example, a simple push-down automaton system that matches open and closing parentheses can be partly "learned" by such LSTM systems; however, if they are trained on strings with an even number of paired open/close parentheses, they fail completely (guess randomly) on odd numbers of paired open/close parentheses. In contrast, the grammar for such strings covers all such cases very simply and much more compactly.

Finally, in research sponsored by Moody's Investor Services, Professor Berwick's group developed a system that can automatically detect poorly written financial analyst reports via syntactic means and then correct them in a manner that appears to be superior to existing grammar checking and style checking commercial systems. Work in this area is ongoing.

Audun Botterud

Audun Botterud has been a principal research scientist in LIDS since September 2016. He is also (as of April 2018) a research affiliate in MIT's Center for Energy and Environmental Policy Research, and he holds a co-appointment at the Argonne National Laboratory. The main goal of Botterud's research is to improve understanding of the complex interactions among engineering, economics, and policy in electricity markets and ultimately enable the transition to a cost-efficient and reliable low-carbon energy system. Towards this end, he uses analytical methods from operations research and decision sciences combined with fundamental principles of electrical power engineering and energy economics. At a more general level, his research focuses on decision making under uncertainty in complex systems.

Grid Integration of Renewable Energy

The rapid expansion of wind and solar energy resources in the power grid gives rise to challenges in the operation and planning of the grid. In the past year, Botterud has been investigating electricity market design questions that arise from more renewables on the grid, particularly from the perspective of long-term investment planning. He has analyzed (with student Conleigh Byers) the design and functioning of so-called capacity markets, whose objective is to ensure that sufficient generation capacity is available to meet demand. Also, Botterud, student Ian Schneider, and principal research scientist Mardavij Roozbehani have used game theory to analyze the need for mandatory participation of consumers in capacity markets, and they have built models to investigate the interaction between generation investment decisions and capacity and energy markets.

In addition, Botterud is analyzing the role of distributed energy resources in the energy system. In particular, he and visiting student Andreas Fleischhacker have developed models for local sharing of solar photovoltaics and energy storage, comparing outcomes from Stackelberg games and social surplus optimization. Moreover, Botterud and students Scott Burger and Ian Schneider are revisiting traditional electricity tariff designs to provide efficient incentives for distributed energy resources.

Two new projects with an international focus have recently been initiated in the grid domain, one focusing on the role of renewable energy and natural gas in India (with student Ivan Rudnick) and the other involving the potential transition to a low-carbon energy system in Italy (with postdoc Mehdi Jafari).

Energy Storage Analytics

Energy storage holds the promise of solving multiple problems in the power grid but is still considered an expensive technology relative to competing solutions. In the past year, Botterud has worked with multiple collaborators on the potential use of energy storage in current and future electricity markets. A new direction for this energy storage analytics work is factoring in empirical laboratory test results in model development and parameter tuning for power grid optimization models. In turn, by providing laboratory testing schemes for more realistic grid conditions, insights from the power grid can be used to guide early-stage laboratory work on promising battery chemistries. These directions are being investigated in a MITEI-funded project (with Professor Fikile Brushett of the Department of Chemical Engineering) with a specific focus on flow batteries. From a commercial perspective, there are a number of open regulatory questions regarding treatment of energy storage in electricity markets. In February 2018, the Federal Energy Regulatory Commission issued a new order on the role of energy storage in electricity markets that cited the research team's inputs and advice in the regulatory proceedings.

There is extensive interest in energy storage among research sponsors at MIT, and several new projects are underway. As an example, in one new project, Botterud and his collaborators are looking at the role of energy storage in distributed and isolated power systems. Their focus is on ways in which different battery technologies may contribute to meeting cost, emissions, and reliability goals.

Guy Bresler

Bonnie and Marty Tenenbaum Assistant Professor Guy Bresler works in information theory, statistics, and applied probability. Specifically, his research aims to understand the relationship between the combinatorial structure and computational tractability of high-dimensional inference in graphical models and other statistical models.

In joint work with student Matthew Brennan and postdoc Wasim Huleihel, Professor Bresler has investigated the interplay between computational and statistical limits in statistical inference problems. The prototypical high-dimensional statistics problem entails finding a structured signal in noise. Many such problems exhibit an intriguing phenomenon: the amount of data needed by all known computationally efficient algorithms far exceeds what is needed for inefficient algorithms that search over all possible structures. A line of work initiated by Quentin Berthet and Phillippe Rigollet has aimed to explain these statistical-computational gaps by reducing from conjecturally hard average-case problems in computer science. However, the delicate nature of average-case reductions has limited the applicability of this approach. Using natural problems as intermediates, Brennan, Bresler, and Huleihel introduced several new techniques to provide a web of average-case reductions showing strong computational lower bounds based on the planted clique conjecture. They also provided algorithms matching the lower bounds and identified the information-theoretic limits of the models considered.

With postdoc Mina Karzand, Professor Bresler has studied the problem of estimating the parameters of a graphical model with a known structure from samples such that posteriors computed via the model are accurate. Focusing on tree-structured binary Markov random fields (Ising models), their main result is a sharp characterization of the dependence on the number of samples needed for all pairwise marginals (and hence posteriors of one variable given another) to be accurate. This result implies that prediction error is bounded uniformly, with no dependence on the strength of interactions, in sharp contrast to the situation for learning the exact graph structure. The main challenge is that errors in estimating parameters across edges can accumulate when marginals involving far-apart nodes are computed. Nevertheless, this effect is counterbalanced by a decay of correlations at exactly the correct scale. Bresler and Karzand also generalized their findings to marginals of arbitrary order, again with a tight characterization of sample complexity.

Professor Bresler and his doctoral student Dheeraj Nagaraj considered the problem of testing for network structure from only a single sample, a common scenario (such as in voting). A single sample is not sufficient to learn network structure or even to determine with any confidence the presence of a single edge; nevertheless, it is possible to ascertain whether the graph underlying the model generating the sample has a nontrivial structure. Bresler and Nagaraj described conditions under which such testing is possible in terms of the natural parameters of the model. Their methodology also applies to other natural settings including testing of random graph distributions.

In a paper Professor Bresler co-authored with graduate student Frederic Koehler and MIT professors Ankur Moitra and Elchanan Mossel, it was shown that a certain influence function in ferromagnetic Ising models is submodular. The main focus of the paper was more general; it addressed a class of models known as restricted Boltzmann machines (RBMs), which have wide-ranging applications in dimensionality reduction, collaborative filtering, topic modeling, feature extraction, and deep learning. The paper proposed a simple greedy algorithm based on influence maximization to learn ferromagnetic RBMs with bounded degrees. More precisely, the algorithm learned a description of the distribution on the observed variables as a Markov random field. The analysis was based on tools from mathematical physics that were developed to show the concavity of magnetization. The group's algorithm extends in a straightforward manner to other ferromagnetic Ising models with latent variables.

Luca Carlone

Luca Carlone started as an assistant professor in the Department of Aeronautics and Astronautics and as a principal investigator in LIDS in 2017 after being a postdoctoral associate and a research scientist in LIDS. The main goal of his research is to enable human-level perception and understanding of mobile robotics platforms (e.g., micro aerial vehicles, self-driving vehicles, ground robots) operating in the real world.

Human-level perception is crucial to enable safety-critical applications of robotics and autonomous vehicles and provides opportunities to enhance efficiency and effectiveness in service robotics and consumer applications (manufacturing, health care, domestic robotics, augmented reality). Toward these aims, Professor Carlone's work involves a combination of rigorous theory and practical implementations. In particular, his research interests include nonlinear estimation, numerical and distributed optimization, and probabilistic inference applied to sensing, perception, and decision making in single- and multi-robot systems.

Provably Correct Robot Perception

Traditional algorithms for robot perception, particularly robot localization and mapping, are fragile and rely on careful parameter tuning. Moreover, they are prone to failure in off-nominal conditions (e.g., large sensor noise, outliers). Professor Carlone recently demonstrated that, using tools from nonlinear optimization (e.g., convex relaxation, Lagrangian duality), graph theory (e.g., cycle space, spectral graph theory), Riemannian geometry, and probabilistic inference, one can design faster and provably correct perception algorithms that are less sensitive to parameter tuning and adverse environmental conditions. These algorithms have been implemented in popular robotics software libraries and used by universities and companies. Robust perception algorithms relax the requirement of human supervision, making robot deployment less expensive and enabling scaling to large teams of cooperative robots in real scenarios. During the past year, Professor Carlone developed novel convex relaxations that can tolerate the presence of spurious measurements. These algorithms have the potential to impact safety-critical applications of robotics, including intelligent transportation, search and rescue, and disaster response. In order to promote the transition of the algorithms to real-world implementations, Professor Carlone became involved in the DARPA Subterranean Challenge, where his team (led by the National Aeronautics and Space Administration and the California Institute of Technology) has been selected and funded to compete in the prestigious competition.

Task-Driven Attention and Co-Design under Resource Constraints

The human brain can extract conceptual information from an image in a time lapse as short as 13 milliseconds. Humans can seamlessly process large amounts of sensory data in everyday tasks such as driving a car on a highway and walking on a crowded street. This efficiency in processing the large amount of data we are confronted with is due to our ability to prioritize some aspects of the visual scene while ignoring others. One can imagine that sensory inputs compete to have access to the limited computational resources of our brain. These resource constraints are dictated by the fixed amount of energy available to the brain as well as time constraints imposed by time-critical tasks. Visual attention is the cognitive process that allows humans to parse a large amount of visual data by selecting relevant information and filtering out irrelevant stimuli. During the past year, Professor Carlone has worked on a computational framework for visual attention and developed algorithms to select the most relevant visual stimuli. These algorithms are linearly complex in terms of number of stimuli, and ensure near-optimal selection of visual clues by leveraging results related to optimization of approximately submodular functions. This effort was complemented by low-power implementations of vision-based algorithms on specialized hardware in collaboration with MIT professors Sertac Karaman and Vivienne Sze.

While “attention” allows optimizing resource utilization during online operations, offline design and allocation of resources to the different modules of a robotic platform is known as co-design. Over the past year, Professor Carlone has studied the co-design problem and developed computational tools to design the controller, estimation, and sensing modules within a linear quadratic Gaussian (LQG) control framework. This work, carried out in collaboration with Professor Ali Jadbabaie, led to the first practical algorithms to select sensory inputs in a control-driven fashion in the presence of resource constraints.

Joint Semantic, Geometric, and Physical World Understanding

Recent years have seen impressive progress in spatial perception; for example, simultaneous localization and mapping (SLAM) has been instrumental in transitioning robots from the factory floor to unstructured environments. Surprisingly, however, SLAM has advanced mostly in isolation from the recent equally impressive progress in object recognition and scene understanding enabled by structured models and deep learning. Few approaches combine spatial and semantic information despite the tremendous scientific and practical promise of hybrid representations. Professor Carlone and his colleagues have been steering the attention of the research community toward this topic by organizing workshops at the top international robotics conferences, giving invited presentations, and writing position papers. During the past year, Professor Carlone worked with a visiting student, Antoni Rosinol, to develop algorithms that enable a robot to understand the high-level structure of an environment from visual-inertial data streams. He also worked with his student Siyi Hu to develop semidefinite relaxations as a means of obtaining efficient near-optimal approximations for intractable problems emerging in semantic understanding. This line of research is partially funded by the US Army Research Laboratory and MIT's Lincoln Laboratory.

Munther Dahleh

Professor Dahleh, director of the Institute for Data, Systems, and Society and the William A. Coolidge Professor of Electrical Engineering and Computer Science, focuses on machine learning with applications in neural learning and control.

Neural Limits in Tracking High-Bandwidth Movements

Generation of high-bandwidth movements during sensorimotor control is fundamentally limited by the number of neurons devoted to the task, their ability to transfer information about the intended movements, and the dynamics of the muscles involved. Yet, these factors and corresponding tradeoffs have not been quantified rigorously. Professor Dahleh and his collaborators used feedback control principles to identify limitations in the ability of the sensorimotor control system to track intended fast movements. They began with a simple closed-loop model in which N integrate-and-fire neurons actuate a combination of agonist and antagonistic muscles under visual and proprioceptive feedback. The input to the motor system is assumed to be a sinusoidal signal that conceptually characterizes the motor intent stimulus likely generated in parietal regions during back-and-forth movements. The frequency of this sinusoidal signal captures the speed of the intended movement. The intended movement signal is fed into N neurons that innervate a muscle model, the output of which is considered to be the trajectory generated by the muscle. Dahleh and his group identified undesirable phenomena at the output when the sinusoidal signal was above a certain frequency. This translates to the output "skipping" cycles during the back-and-forth movement.

Using tools in signal processing and nonlinear control theory, Professor Dahleh and his collaborators analyzed the fundamental limits of this feedback loop. They first identified an effective pair of integrate-and-fire neurons that capture the effects of the N neurons. For this pair of neurons, they then derived explicit conditions on the neurons' ability to transfer information about the input and the neuron and muscle dynamics under which the undesirable phenomena might exist. The maximum attainable frequency depends on muscle and feedback dynamics as well as N and neuronal dynamics. The group built upon new theory developed using feedback control principles and an appropriately simplified model of the sensorimotor control system to identify how number of neurons, neural dynamics, delays, muscles, and feedback might interact during generation of fast movements. If one component is compromised, we can take advantage of the other components to restore motor performance with an assistive neuroprosthetic device. This work has applications for helping stroke patients with corticospinal injuries who can no longer move quickly, as well as applications in the performance of brain-machine interfaces for prosthetic devices.

Minimal Realization and Learning Problems for Lump Linear Systems

This work addresses two fundamental problems in the context of jump linear systems. The first problem is characterizing the minimal state space dimension solely from input-output pairs without any knowledge of mode switches. The second problem is characterizing the system's number of discrete modes. To address the first problem, Professor Dahleh and his collaborators developed a linear system theory approach and constructed an appropriate Hankel-like matrix. The rank of this matrix provides the state space dimension. With respect to the second problem, they showed that the minimal number of modes corresponds to the minimal rank of a positive semidefinite matrix obtained by linearly transforming an output tensor. Such characterizations are then used to construct robust learning algorithms from finite data.

Jonathan How

Professor How leads research efforts focused on the control of multiple autonomous agents, with an emphasis on distributed decision making under uncertainty; path planning, activity, and task assignment; mission planning for unmanned aerial vehicles (UAVs) and unmanned ground vehicles; sensor network design; and robust, adaptive, and nonlinear control. Professor How is also the principal investigator for the Aerospace Control Laboratory (ACL). Recent research includes the following.

Optimal Communication Planning for Distributed Loop Closure Detection

Multi-robot or cooperative simultaneous localization and mapping (CSLAM) is an active area of research with a wide spectrum of applications that span from robotic search and rescue in challenging environments to navigating fleets of autonomous cars. Communication is a crucial aspect of the approach, without which CSLAM would simply reduce to decoupled copies of conventional simultaneous localization and mapping. Due to the distributed nature of the problem, detecting inter-robot loop closures (i.e., distributed place recognition) necessitates sharing sensory data with other robots. A naive approach to data sharing can easily lead to a waste of mission-critical resources. Professor How and his collaborators proposed a general, resource-efficient communication planning framework for inter-robot loop closure detection that takes into account both the total amount of exchanged data and the induced division of labor between the participating robots. The team described a fast algorithm for finding globally optimal data exchange policies and provided a theoretical analysis to characterize the necessary and sufficient conditions under which simpler unidirectional strategies ("monologs") are optimal. This framework is able to verify the same set of potential inter-robot loop closures as other state-of-the-art approaches while exchanging considerably less data and influencing the induced workloads.

Cross-Modal Reinforcement Learning

Intelligent agents should be capable of disambiguating local sensory streams to realize long-term goals. In recent years, combined progress in computational capabilities and algorithmic innovations has afforded reinforcement learning approaches the ability to achieve these desiderata in impressive domains, exceeding expert-level human performance in durative tasks such as Atari 2600 games and board games such as Go. Nonetheless, many of these algorithms thrive primarily in well-defined mission scenarios learned in isolation from one another; such monolithic approaches are not sufficiently scalable for missions in which goals may be less clearly defined, and sensory inputs found to be salient in one domain may be less relevant in another. ACL researchers recently introduced the Cross-modal Attentive Skill Learner (CASL), a new framework for multi-sensory learning integrated with hierarchical reinforcement learning to enable learning high-level policies that are transferable across tasks. This work provides concrete examples wherein the cross-modal attentive approach not only improves performance in a single task but accelerates transfer to new tasks. Experiments demonstrate that the introduced cross-modal attention mechanism anticipates and identifies useful latent features while filtering irrelevant sensor modalities during execution. As a final contribution, the Arcade Learning Environment, a standard and popular Atari-based reinforcement learning benchmark, has been modified to support audio queries, with evaluations conducted to show the benefits of cross-modal learning in several games.

Transferable and General Model of Pedestrian Motion Prediction

Intention recognition of pedestrians is crucial to the safe and reliable working of autonomous vehicles. Professor How and his collaborators have proposed a context-based model of motion prediction, CASNSC, to predict pedestrian behaviors at crowded intersections. The team incorporated semantic features from the environment to improve prediction of pedestrian trajectories at intersections and busy streets. Adding the environmental context, when available, not only makes prediction more robust but can also provide increased flexibility of prediction in new environments. The researchers also created a transferable framework that they call TASNSC, which accurately predicts pedestrian trajectories even in new intersections on which it has not been trained. This innovation was achieved by making use of the contravariant components of trajectories in the curbside coordinate system, ensuring that the transformation of trajectories across intersections is affine regardless of the curbside geometry. Furthermore, the proposed model can be generalized to different domains with different geometries, allowing either collective or incremental learning when entering a new environment. Professor How and his collaborators demonstrated improvement in prediction accuracy in the case of train and test intersections. Furthermore, they showed that the prediction performance of TASNSC was comparable when trained and tested on different intersections and trained and tested on the same intersection. To train their models, they built two data collection platforms to record pedestrian trajectory data using cameras and LiDAR sensors. These platforms provided a large pedestrian data set that will be useful for researchers in human motion behavior studies.

Decentralized Dynamic Task Allocation for Mobile Robots

In time-sensitive and dynamic missions, multi-UAV teams must respond quickly to new information and objectives. Previous methods required fully resolving the initial task allocation team, which can be prohibitively slow, especially in highly dynamic environments and poor communication settings. To respond to new tasks, Professor How and his collaborators developed algorithms that can reuse information and solutions, modifying existing allocations to allocate new tasks; specifically, they designed the partial replanning consensus-based bundle algorithm (CBBA), a decentralized task allocation algorithm that allows for fast allocation of new tasks without full reallocation of existing tasks. In addition, CBBA with partial replanning enables the team to trade off between convergence time and increased coordination by resetting a portion of the previous allocation at every round of bidding on tasks. By resetting the last tasks allocated by each agent, the researchers were able to ensure the convergence of the team to a conflict-free solution.

On-Orbit Mass Property Estimation for the Space Shuttle Orbiter

Professor How and his collaborators revisited a strategy for online selection of attitude control thruster inputs used during mass property estimation of the space shuttle. Previous approaches utilized a second-order extended Kalman filter along with a control selection algorithm that selects from a list of possible thruster inputs in order to maximize the decrease in estimation covariance. The group outlined problems with the existing strategy that occur when the magnitudes of thruster inputs are not known with sufficient accuracy. They also described methods for increasing estimation accuracy by modifying the weighting matrix used in the control selection algorithm and enforcing control input diversity. The results indicate that these methods can be beneficial in cases in which the thrust magnitude and thruster on-time are highly variable.

Marija Ilic

Marija Ilic is a permanent senior staff member of MIT’s Lincoln Laboratory, a visiting professor in IDSS, and a principal investigator in LIDS. She has proactively worked toward building a collaboration among Lincoln Laboratory Group 73, LIDS, IDSS, and MITEI. She has done so by organizing and participating in several meetings with current and potential industry sponsors and by presenting her work and vision at workshops on electric energy systems. Professor Ilic is leading projects in major research areas such as modeling and control for changing electric energy systems, resiliency, and electricity markets. She advises three EECS doctoral students and serves as a co-advisor to a MITEI postdoc jointly with Francis O’Sullivan. She is the PI on three LIDS projects and a technical lead on several Lincoln Laboratory projects.

Professor Ilic served on an invited panel (System Engineering Needs and Challenges Generated by Electrification of Air Vehicles) at the 2018 American Institute of Aeronautics and Astronautics/Institute of Electrical and Electronics Engineers (AIAA/IEEE) Electrical Aircraft Technologies Symposium. In June, at the Transactive Energy Systems Conference in Cambridge, she presented an invited talk titled “Transactive Energy Research at MIT.” Transactive energy is a direct outgrowth of the homeostatic control concept conceived many years ago by the late Fred Schweppe and is currently being pursued as the basis for electricity retail markets. Professor Ilic was also an invited plenary speaker at the North American Power Systems Symposium; her talk was titled

"Toward Assessing Effects of New Technologies in Electric Energy Systems: New Modular Modeling and Simulation Paradigm."

Professor Ilic served as the technical lead on a study funded by the Department of Homeland Security and the RAND Corporation that focused on candidate power grid architectures for future Puerto Rico electricity services. This study has been documented in two Lincoln Laboratory technical reports.

Ali Jadbabaie

Professor Jadbabaie led a recent multi-investigator project sponsored by DARPA on the fundamental limits of machine learning. The project, which involved eight PIs from LIDS, resulted in theoretical and algorithmic advances that opened the "machine learning black box" and provided a foundational theory to understand fundamental limits in high-dimensional data problems and develop scalable methods for achieving these limits. The project brought together experts in statistics, machine learning, optimization, algorithms, and applications. The first thrust of the project led to new approaches for learning in graphical models and causal inference and to a rigorous characterization of statistical and computational tradeoffs. The second thrust led to new approaches for sequential prediction and online learning as well as methods for distributed large-scale optimization as it applies to large-scale machine learning problems. The final thrust produced new tools for recommendation systems and showed how techniques from matrix estimation and prediction can lead to state-of-the-art algorithms that can significantly improve the quality of such systems.

Additionally, Professor Jadbabaie's work as part of a multi-investigator university research initiative funded by the Army Research Office has led to a new understanding of decision making in groups. In particular, together with former doctoral student Amin Rahimian and Professor Elchanan Mossel, Jadbabaie addressed the computations that rational agents in a network undertake in an opinion exchange model wherein they repeatedly act on private information, taking actions that maximize expected utility. The researchers showed that such computations are hard in a precise sense, even in the simplest scenarios. While behavioral economists have provided experimental evidence that rational decision making is outside the cognitive limit of individuals in group decision scenarios, these results are the first to formally show that such problems are hard in an algorithmic sense, even for computers.

In other work, Professor Jadbabaie and former graduate students studied a family of information aggregation and social learning models in which individuals combine their private information and the opinions of their social peers to learn an unknown state of the world. They showed conditions and environments that are conducive to learning, even when individuals are not fully rational and cannot maintain a full history of past observations and actions.

Patrick Jaillet

The research of Professor Jaillet (Dugald C. Jackson Professor of Electrical Engineering and Computer Science and ORC co-director) and his group focuses on online optimization and learning. In particular, they address online and dynamic versions of assignment/matching, secretary, and routing problems as well as some of their generalizations. Their research deals with provable results (algorithmic design and analysis) on how to solve such problems under uncertainty, with or without explicit stochastic modeling of uncertainty. Methodological tools include those from online optimization (competitive analysis), stochastic optimization (robust analysis), online learning (min-max regret analysis, Bayesian updates), game-theoretic concepts (price of anarchy), and their integrations.

Motivating applications include routing and location problems that arise from transportation and logistics networks as well as dynamic resource allocation problems in various applications arising from the digital economy (search engines and online auctions), health care (kidney exchange programs), and social interactions (job search and house exchanges).

Professor Jaillet's research group at MIT this past academic year included seven doctoral students from ORC (Maximilien Burq, Phillip Chodrow, Chong Yang Goh, Virgile Galle, Sebastien Martin, Konstantina Mellou, and Julia Romanski) and four students from the MIT Leaders for Global Operations graduate program (Scott Foster, Lila Fridley, Abishek Tambat, and Jonathan Zanger). His research group in Singapore included two postdocs (Jie Chen and Supriyo Ghosh from SMART) and six doctoral students (Zhongxiang Dai, Phong Nguyen, and Haibin Yu from the National University of Singapore; Anatoliy Prokhorchuk from Nanyang Technological University; Meghna Lowalekar from Singapore Management University; and Gary Goh from the Singapore University of Technology and Design).

Funded research programs over the past academic year originated from the Office of Naval Research (Online Optimization and Learning under Uncertainty And Decentralized Online Optimization in Multi-Agent Systems in Dynamic and Uncertain Environments) and SMART (Future Mobility, a large project involving several other MIT principal investigators).

Sertac Karaman

Professor Karaman, the Class of 1948 Career Development Chair, carries out research in the areas of control theory, optimization, formal methods, stochastic processes, and applied probability, with applications to robotics, mobile sensor networks, cyber-physical systems, and dynamic data-driven application systems. His current work focuses on computing for complex, agile autonomous vehicles.

High-Dimensional Computing for Autonomous Systems

A number of problems in autonomy are plagued by the curse of dimensionality: the computational effort required to solve many problems of inference, estimation, control, and learning scales exponentially with increasing number of variables describing the state of the underlying system. In recent work, Professor Karaman and his collaborators proposed novel algorithms that run in polynomial time for all problem instances admitting a particular low-rank structure. The key insight involves compressing a certain cost-to-go function (as in data compression) and working on the compressed version of the function iteratively, in order to improve it towards an optimal one. This year, using the same insights, they developed new algorithms that handle complex differential games involving multiple agents with high-dimensional state space representations and nonlinear differential constraints. In addition, they developed novel tensor decompositions, specifically a tensor ring representation that significantly improves the scaling of memory and time required for computing with high-dimensional structures.

High-Throughput Computing for Autonomous Systems

Being able to perceive its environment is of utmost importance to any robotic vehicle. However, most robot perception problems are high-dimensional large-scale inference problems (e.g., due to high-rate sensing data). Professor Karaman and his collaborators designed task-driven perception algorithms that implement attention mechanisms to extract the most meaningful data set enabling efficient perception. This year, they developed integrated control and perception algorithms that can handle high-rate, high-resolution sensory data while retaining the provable guarantees of both control and perception. They demonstrated the algorithms in the new laboratory environment in MIT's Building 31, which was recently renovated to include a large motion-capture room. The room was equipped with 40 high-rate motion-capture cameras and showcased the team's algorithms in a fully autonomous drone racing experiment in which the drones reached speeds of up to 20 miles per hour in a complex environment.

Low-Energy Computing for Autonomous Systems

Computers that can enable fingernail-sized flapping-wing robotic vehicles or control small insects must run under tight energy budgets. A state-of-the-art insect-sized flapping-wing robotic vehicle requires 100 milliwatts of power to lift itself. Unfortunately, state-of-the-art general-purpose computers need at least two orders of magnitude more power to run algorithms that make such robotic vehicles autonomous. Collaborations with the Energy-Efficient Multimedia Systems Group in the Microsystems Technology Laboratories resulted in the first complete visual-inertial state estimation chip.

Autonomy-Enabled Transportation Systems

Autonomous vehicles hold the potential to revolutionize transportation, particularly in urban centers. For example, drones may enable the next generation of high-throughput, low-delay urban logistics services. This research area aims to better understand the potential impact of autonomous vehicles by studying new autonomous vehicle systems. For instance, one potential technology allows trucks to follow each other closely, much closer than what human drivers can safely achieve. This year, Professor Karaman and his colleagues developed a new analysis to better understand the efficiency-sustainability tradeoff of autonomous vehicles. Furthermore, in joint work with Professor Steven Barrett of the MIT Laboratory for Aviation and the Environment, they used satellite data to study the impact of air transportation on the environment. They are now considering the positive environmental impact that autonomy-enabled air transportation can enable.

Sanjoy Mitter

Professor Mitter continued his research on various aspects of information theory as they relate to control in environments where sensors, actuators, and controllers are linked by noisy communication channels. In the paper "LQG Control with Minimum Directed Information: Semidefinite Programming Approach," Mitter and his co-authors considered a discrete-time LQG problem wherein the directed information from the observed output to the control input is minimized with the constraint that a certain level of control performance is obtained. Such ideas are fundamental to networked control systems. Professor Mitter is also focusing on generalizations to fully networked environments. In other research, he is investigating simulated annealing by studying the asymptotic behavior of gradient stochastic differential equations with an additional velocity term.

Eytan Modiano

Professor Modiano (associate director of LIDS) leads the Communications and Networking Research Group (CNRG), which consists of eight graduate students. The primary goal of CNRG is the design of architectures for communication networks that are cost effective and scalable and meet emerging needs for reliable, high-data-rate communications. In recent years, the group has focused on robust network designs, wireless networks, data center networks, and interdependent cyber-physical networks.

During the past year, CNRG members authored more than two dozen journal papers and conference papers. Their contributions included the design of transmission scheduling schemes that optimize "information freshness" in wireless networks, the design of control algorithms for networks in adversarial environments, and work on robustness in interdependent networks.

Future IoT applications will increasingly rely on exchange of delay-sensitive information for monitoring and control. Application domains such as autonomous vehicles, command and control systems, virtual reality, and sensor networks rely heavily on distribution of time-critical information. Age of Information (AoI) is a recently proposed metric that captures the freshness of information from the perspective of the application. AoI measures the amount of elapsed time from the moment the most recently received packet was generated to the present time. In recent years, CNRG has been developing network algorithms for optimizing AoI in wireless networks. During the past year, two papers authored by CNRG members on this topic received best paper awards at leading conferences in the field: "Optimizing Age of Information in Wireless Networks with Throughput Constraints," by Igor Kadota, Abhishek Sinha, and Eytan Modiano, received the 2018 IEEE INFOCOM (International Conference on Computer Communications) Best Paper Award, and "Optimizing Information Freshness in Wireless Networks under General Interference Constraints," by Rajat Talak, Sertac Karaman, and Eytan Modiano, received the 2018 Association for Computing Machinery (ACM) MobiHoc Best Paper Award.

Over the past decade, CNRG has developed a number of network control algorithms for communication networks, wherein the objective is usually to maximize network throughput or utility. The effectiveness of these algorithms typically relies on the premise that the network dynamics are stochastic. However, increasingly networks operate in environments where network dynamics are non-stationary or even adversarial. For example, modern communication networks frequently suffer from distributed denial-of-service attacks or jamming attacks, in which traffic injections and channel conditions are controlled by a malicious entity in order to degrade network performance. During the past year, the group developed network control algorithms that optimize network performance in adversarial settings. In particular, they developed network routing and scheduling schemes that provide guaranteed performance under worst-case (adversarial) network dynamics.

The group continues to work on the robustness of interdependent networks as well. Many engineering systems involve interactions between two or more networked systems. Cyber-physical systems, for example, consist of networked computer systems that are used to control physical systems such as the power grid, water or gas distribution systems, and transportation networks. While this cyber-physical interaction is critical for the functionality of the overall system, it also introduces vulnerabilities in the form of interdependence failure cascades, wherein failures in the cyber network lead to failures in the physical network, and vice versa. Over the past year, Professor Modiano and his student Jianan Zhang have studied the interdependence between power grid and communication networks and developed power grid control algorithms that are robust to interdependence failures.

In recent years, the group has also been pursuing industrial collaborations in order to increase the impact of their work on practical systems. Over the past year, the group collaborated with researchers at Nokia Bell Labs on the problem of resource allocation in distributed computing networks. In addition, the group is involved in a joint project with BBN Technologies on resilient overlay networks, a project with Qualcomm on mission-critical communications, and a collaboration with researchers at Lincoln Laboratory on the design of network architectures and protocols for military communications.

CNRG's research crosses disciplinary boundaries by combining techniques from network optimization, queueing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Asuman Ozdaglar

Professor Ozdaglar is the head of the Department of Electrical Engineering and Computer Science. Her research group focuses on modeling, analysis, and optimization of large-scale, dynamic multi-agent networked systems. The group's research draws on advances in game theory, optimization theory, dynamical systems, and stochastic network analysis. It focuses on both investigating substantive problems in these areas and developing new mathematical tools and algorithms for the analysis and optimization of these systems and for processing large-scale data.

Pablo A. Parrilo

Professor Parrilo and his research group are focused on mathematical optimization, systems theory, and control, with an emphasis on development and application of computational tools based on convex optimization and algorithmic algebra.

Yury Polyanskiy

Professor Polyanskiy conducts research in the areas of mathematics of information (information theory), coding theory, and the theory of random processes. His current work focuses on non-asymptotic characterization of the performance limits of communication systems, non-Shannon information measures, redundant circuits, and probabilistic methods in combinatorics.

Application of an Information-Percolation Method to Reconstruction Problems

Professor Polyanskiy has proposed a method of proving impossibility results based on applying strong data-processing inequalities to estimate mutual information between sets of variables forming certain Markov random fields. The result is that mutual information between two "faraway" (as measured by graph distance) variables is bounded by the probability of existence of an open path in a bond-percolation problem on the same graph. Furthermore, stronger bounds can be obtained by establishing mutual comparison results through an erasure model on the same graph, with erasure probabilities given by the contraction coefficients. In an application, Professor Polyanskiy and his collaborator showed that the new method provides a sharp threshold for partially recovering a rank-one perturbation of a random Gaussian matrix, recovers (and generalizes) the best-known upper bound on noise levels for group synchronization, and establishes a new impossibility result for k-community detection.

Information Storage in the Stochastic Ising Model

Most information systems store data by modifying the local state of matter, in the hope that atomic (or subatomic) local interactions will stabilize the state for a sufficiently long time, thereby allowing later recovery. Professor Polyanskiy and his collaborators initiated work focusing on information retention in locally interacting systems. The evolution in time of the interacting particles was modeled via the stochastic Ising model. The main goal was to evaluate information capacity when the time t scales with the size of the system n. They showed that data on the order of the square root of n bits can be stored for infinite time (and even with zero error) in horizontally or vertically striped configurations.

One of the main results of this work is an achievability scheme that stores more than the square root of n bits (in orders of magnitude) for superlinear times. The analysis of the scheme decomposed the system into independent Z channels whose crossover probability was found via the Lifshitz law of phase boundary movement. In addition, for the zero-temperature case, optimal characterizations were given for grid dynamics with an external magnetic field and for dynamics over the honeycomb lattice. Professor Polyanskiy and collaborators also provided results for the positive but small temperature regime.

Coherent Multiple-Antenna Block-Fading Channels at Finite Blocklengths

Professor Polyanskiy and collaborators considered a channel model that is often used to describe the mobile wireless scenario: multiple antenna additive white Gaussian noise channels subject to random (fading) gain with full-channel state information at the receiver. The dynamics of the fading process are approximated via a piecewise-constant process (frequency nonselective isotropic block fading). The work of Professor Polyanskiy and his group addresses the finite blocklength fundamental limits of this channel model. Specifically, they give a formula for channel dispersion, a quantity governing the delay required to achieve capacity. The multiplicative nature of the fading disturbance leads to a number of interesting technical difficulties that required the group to enhance traditional methods for finding channel dispersion.

An interesting implication of this work is that dispersion-optimal coding schemes require employing orthogonal designs such as Alamouti's scheme for the multiple-input single-output channel, a surprising observation considering that Alamouti's scheme was designed for reducing demodulation errors rather than improving coding rates.

Broadcasting on Bounded Degree Directed Acyclic Graphs

Professor Polyanskiy and his collaborators studied a generalization of the well-known model of broadcasting on trees: an infinite directed acyclic graph (DAG) with a unique source node. The goal was to recover the original bit with a probability of error better than one half from the values of all nodes at an arbitrarily deep layer k.

In addition to its natural broadcast interpretation, the DAG broadcast is a natural model of noisy computation. Some special cases of the model represent information flow in biological networks, and other cases represent noisy finite automata models.

Professor Polyanskiy's group showed that there exist DAGs with bounded degree and layers of size that permit recovery provided d is sufficiently small, and they found the critical δ for the DAGs constructed. Their results demonstrate a doubly exponential advantage for storing a bit in bounded degree DAGs relative to trees. On the negative side, they showed that if the DAG is a two-dimensional regular grid, recovery is impossible for any δ in (0, ½) if all nodes use either AND or XOR for their processing functions.

Beta-Beta Bounds: Finite-Blocklength Analog of the Golden Formula

It is well known that the mutual information between two random variables can be expressed as the difference of two relative entropies that depend on an auxiliary distribution, a relation sometimes referred to as the golden formula. This work is concerned with a finite-blocklength extension of this relation that consists of two elements: a finite-blocklength channel-coding converse bound that involves the ratio between two Neyman-Pearson b functions (beta-beta converse bound) and a novel beta-beta channel-coding achievability bound, expressed again as the ratio between two Neyman-Pearson b functions.

To demonstrate the usefulness of this finite-blocklength extension of the golden formula, Professor Polyanskiy and his group used beta-beta achievability and converse bounds to obtain a finite-blocklength extension of Verdu's wideband-slope approximation. The proof parallels the elegant derivation outlined by Verdu, with the beta-beta bounds used in place of the golden formula.

Sample Complexity of Population Recovery

The problem of population recovery refers to estimating a distribution based on incomplete or corrupted samples. Consider a random poll of sample size n wherein each individual is asked to answer d binary questions. Professor Polyanskiy and his colleagues considered the following two polling impediments: (1) in lossy population recovery, a respondent may skip each question with probability ε, and (2) in noisy population recovery, a respondent may lie on each question with probability ε. Given n lossy or noisy samples, the goal is to estimate the probabilities of all 2^d binary vectors simultaneously within accuracy δ with high probability.

This work settles the sample complexity of population recovery. For the lossy model, the optimal sample complexity improves the state of the art in several ways: a lower bound is established, the upper bound is improved, and the result depends at most on the logarithm of the dimension. Surprisingly, the sample complexity undergoes a phase transition from parametric to nonparametric rate when ε exceeds ½. For noisy population recovery, the sharp sample complexity turns out to be more sensitive to dimensions and scales with the exception of the trivial cases of $\varepsilon = 0$, ½, or 1.

For both models, the estimators simply compute the empirical mean of a certain function found by pre-solving a linear program (LP). Curiously, the dual LP can be understood as Le Cam's method for lower bounding the minimax risk, thus establishing the statistical optimality of the proposed estimators. The value of the LP is determined via complex analytic methods.

Alexander Rakhlin

Professor Rakhlin joined MIT in January 2018 after spending eight years in the Department of Statistics at the University of Pennsylvania. His research resides at the intersection of statistics, machine learning, and optimization. This past year, he pursued two main directions of research.

Online Prediction

In the problem of online prediction, the forecaster is tasked with making accurate predictions of a sequence without stochastic assumptions on its evolution. Rakhlin and his colleagues' main contribution to the area is a new fundamental interconnection among online prediction, martingales, and the Burkholder method. Using these new techniques, they developed the first known optimal and computationally efficient prediction method for online matrix completion.

Neural Networks

The second thrust of Professor Rakhlin's research is on understanding statistical properties of neural networks as well as their optimization landscape. In joint work with his colleagues, Rakhlin established the first known size-independent sample complexity bounds for neural networks. Also in joint work, he has studied neural networks through the lens of information geometry. His group defined a notion of a Fisher-Rao norm and showed that it serves as a common starting point for many other measures of complexity studied in the literature. In a recent development with other colleagues, Rakhlin showed that the classical Nadaraya-Watson estimator with a particular choice of a kernel can interpolate data yet attain optimal out-of-sample performance. This work suggests that interpolating methods such as over-parametrized neural networks need not "overfit" from a theoretical point of view.

Mardavij Roozbehani

Principal research scientist Roozbehani led several research efforts related to mathematical modeling, optimization, and control for cyber-physical networked systems. Application areas of focus included energy networks and transportation networks. The main themes in Roozbehani's research are concentrated around models and methodologies for quantifying robustness, efficiency, and risk in energy networks and understanding the tradeoffs that system architectures induce between these metrics. For instance, in energy networks with price-sensitive demand and renewable (uncertain) supply, Roozabehani and his collaborators' research revealed important tradeoffs between efficiency and risk and how they depend on the extent of cooperation versus competition among participating agents. Market mechanisms that a system operator can adopt to influence behavior and strike optimal tradeoffs were obtained as by-products of the tradeoff characterization. Development of abstract analytical models at both the agent and network levels for modeling the dynamic interaction between agents and markets, as well as strategic interactions among agents, has been instrumental in producing the above-mentioned findings and an important thrust of this research in general. These abstractions guided Roozbehani's research in cyber-physical systems and resulted in deeper insights on and a better understanding of the robustness and fragility of general flow networks. A specific example of such generalization is control design for increasing margins of stability and preventing cascaded failures in transportation networks.

Robustness and Fragility of Networked Systems

Roozbehani's joint work with PhD candidate Tuhin Sarkar and Professor Dahleh examined fundamental aspects of robustness and fragility in large-scale infrastructure systems at a more abstract level. This research unified existing but disparate results across several application domains, from economic networks to vehicle platoons and consensus networks, and led to new insights on the role of the Gramian of a dynamical network in robustness and fragility as dimension grows. In particular, the researchers showed that strong asymmetry in the information flow in a directed graph causes the corresponding network to be very fragile to input disturbances. The key feature of this approach is its characterization of the fragility of a large network due to interconnections, which is different from the instability of the network due to the asymptotic vicinity of the eigenvalues of the network matrix to the unit circle.

Market Design for Renewable Resources in Energy Networks

Roozbehani's work with PhD candidate Ian Schneider provided new insights on and quantitative tools for designing markets to integrate renewable energy resources. The analysis and design approach, which builds on principles of game theory and optimization, hinges on careful modeling of bidding behaviors for stochastic resources when energy imbalance payments are determined endogenously from market clearing conditions. In realistic and practical scenarios, demand and wind forecast errors impact the effective price, so the strategic behavior of participants affects the price paid by producers. This feature necessitates a game-theoretic formulation. One of the contributions of this work was novel derivation of producers' bidding strategies through a symmetric subgame perfect equilibrium. This result showed how supply curve convexity and resource correlation can lead wind producers to bid conservatively even when they are not risk averse. The findings also indicate that market-based pricing mechanisms improve tradeoffs between system efficiency and risk in the mean squared bid error sense, as compared with the case in which price levels are determined by alternative policies, suggesting additional benefits of market-based penalty prices beyond those previously outlined in the literature.

Robustness and Risk in Transportation Networks

Roozbehani's work with postdoctoral associate Yasin Yazicioglu on the robustness of transportation networks revealed new sources of fragility in these networks resulting from limited information exchange and decision making based on local observations. This research led to novel and unexpected results wherein locally optimal decisions or local improvements in infrastructure had negative consequences and degraded global performance. These findings paved the way for the development of novel control algorithms for establishing speed limits or alternative incentives in congestion pricing to increase the robustness of transportation networks to disturbances and link failures.

Devavrat Shah

Professor Devavrat Shah and his research group are currently involved in developing theoretical foundations and algorithmic solutions for questions arising in the context of "social" data processing and decision making. Social data, the data generated through modern services including e-commerce portals, media, polls, and more, provide us with a granular lens on the inner workings of our society. On the positive side, they can help in the design of better policies, improve social living by enabling efficient labor markets, and help businesses operate efficiently. On the negative side, they can help manipulate social opinions and, potentially, outcomes of elections. If indeed we believe that election outcomes have been manipulated, it is essential to precisely identify the causes and mechanisms leading to this manipulation so that it can be prevented in the future.

Intellectually, this requires development of robust statistical models that capture the universal aspects of social behavior, the ability to engage in causal inference with extremely limited information in the presence of a large number of potential causes, and algorithms that can scale with the amount of data while extracting meaningful information in high-dimensional settings. Specifically, addressing the challenges just described requires fundamental progress at the interface of statistics, machine learning, computation, and social sciences. Professor Shah's group has been working to address these challenges through their focus on canonical issues in social data processing, including learning choice, recommendations, ranking, crowdsourcing, and causal inference.

Suppose New York State decides to impose a gun control law and, a year later, wants to quantify the impact of the law on the state's crime rate. In such settings, a randomized control trial is infeasible as there is only one New York State, for example. A solution to this is "synthetic control," wherein one views the crime rate in New York State (pre-intervention) as a weighted combination of crime rates in Illinois, California, and Washington. The question is how to produce such a synthetic control in a data-driven manner without the input of experts.

Building on the seminal work of Alberto Abadie and colleagues, Professor Shah's group has developed a "robust" version of a data-driven approach for identifying a synthetic control. The method created as part of this work has been made available through an open source library that has now been used, for example, to understand the impact of policies related to marijuana on opioid consumption. Associated work has led to advances in time series forecasting, and the initial work received an award at the NIPS (Conference on Neural Information Processing Systems) Time Series Workshop 2017.

Suvrit Sra

Professor Sra joined the Department of Electrical Engineering and Computer Science in January 2018; he continues as a researcher at LIDS, where he has been since January 2015. His research spans machine learning and optimization and pure and applied mathematics and statistics.

Professor Sra's primary research is in large-scale optimization for machine learning. In the 2018 academic year, with his collaborators and students, he worked on developing deeper theoretical understandings of foundational topics in optimization and deep neural networks. The past year has seen some new developments by Sra and his collaborators on this topic, as well as follow-up work by colleagues in the machine learning community.

Professor Sra and his group also continued to develop the topic of geometric optimization, a new subarea of mathematical optimization that Sra has been helping to establish on a more solid computational complexity foundation. Over the past year, his work on this topic led to the first accelerated gradient algorithm on manifolds, a quest that he has been pursuing in recent years.

Finally, Professor Sra continues to expand his work on discrete probability theory (determinantal point processes and the richer family of measures called strongly Rayleigh measures).

John Tsitsiklis

Professor Tsitsiklis (LIDS director, IDSS associate director, and Clarence J. LeBel Professor of Electrical Engineering) has been primarily focused on LIDS administrative aspects and on course development for the new MicroMasters in Statistics and Data Science program.

On the research side, he and his students work on system modeling, analysis, optimization, and control in possibly stochastic and dynamic environments and in the possible presence of multiple agents with conflicting interests. Their research activities are focused on developing methodologies, mathematical tools of broad applicability, and computational methods. Additional research directions include basic technical problems in dynamic programming theory and models of systemic risk in the interbank lending system. Motivating applications for recent work have come from domains such as computer networks and social networks. Examples of the group's recent activities are provided below.

Replication Strategies in Data Centers and Other Multiserver Systems

Consider a processing system, consisting of several servers, meant to process a random stream of incoming tasks. A popular strategy that can reduce average delay—both in theory and in practice—involves replicating incoming jobs and sending different copies of the task to different servers. Existing analyses of such schemes point to performance improvements and provide some insights but under very restrictive and unrealistic assumptions. Together with his student Martin Zubeldia, who is co-supervised by Professor David Gamarnik (MIT Sloan), Professor Tsitsiklis has developed a complex analysis that describes in a more realistic manner the random slowdowns in different servers and the correlation of such slowdowns with job size. They are currently carrying out a theoretical study of optimal or near-optimal replication strategies.

Sensitivity Theory for a Class of Hybrid Dynamical Systems

There is a popular (and much used in practice) scheduling policy in computer networks known as the max-weight policy. This policy results in "hybrid" dynamics, whereby the derivative of the state vector is a piecewise constant function of the state. In the presence of stochastic fluctuations of the input to the scheduling system, one obtains perturbed trajectories. Much of the analysis of such policies depends on an understanding of the effect of such perturbations. Together with visiting student Arsalan Sharifnassab, Professor Tsitsiklis has developed a theory on the effect of perturbations for a rather general class of hybrid systems. They then applied it to the special case of max-weight scheduling policies to derive theoretical results stronger than those previously available and to settle some problems that were left open in an earlier LIDS doctoral thesis. During the current year, these results were refined and submitted for publication. Furthermore, progress was made toward a more general understanding of dynamical systems with small sensitivity to additive perturbations.

Caroline Uhler

Henry L. and Grace Doherty Associate Professor Caroline Uhler carries out research in the areas of mathematical statistics and optimization with applications to genomics and cell biology. Her current research is centered around three interconnected pillars, namely causal inference, gene regulation, and early disease diagnostics.

Bayesian Approach to Causal Inference

Traditional causal inference methods often fail in modern applications that exhibit a larger number of variables than data points. The resulting uncertainty about the underlying network and the desire to incorporate prior information recommend a Bayesian approach. But the combinatorial structure of the problem poses a striking inference challenge. Together with Professor Tamara Broderick and doctoral student Raj Agrawal, Professor Uhler proposed a posterior approximation based on the observation that if empirical conditional independence tests are incorporated, the focus can be on a high-probability directed graph. Professor Uhler and her collaborators showed that their method allows the desired flexibility in prior specification, removes the timing dependence on the maximum indegree of current algorithms, and yields provably good posterior approximations; in addition, it was shown to achieve superior accuracy, scalability, and sampler mixing on several data sets.

Causal Inference from Interventional Data

As a result of recent technological developments in genomics that allow the generation of observational and interventional single-cell RNA-seq data at a very large scale (perturb-seq), it is now a fundamental problem to develop a theory of causal inference from a mix of observational and interventional data. Perfect interventions eliminate dependencies between targeted variables and their direct causes (e.g., gene knockouts), while soft interventions only modify dependencies between targeted variables and their causes (e.g., gene knockdowns). Professor Uhler, doctoral student Karren Dai Yang, and Abigail Katcoff from the expanded Undergraduate Research Opportunities Program (SuperUROP) showed, quite surprisingly, that the identifiability results shown with causal DAGs under perfect interventions extend to soft interventions. Importantly, for biological applications, this implies that gene knockdowns provide as much causal information as gene knockouts (at least in the infinite sample regime), although soft interventions are often much easier to perform. Professor Uhler's doctoral student Yuhao Wang and SuperUROP student Chandler Squires developed algorithms for learning the causal model from such data, and these algorithms were presented at NIPS 2017.

Joint Inference of Causal Graphs

In many real-world applications, we have access to data from a collection of causal networks, and we can assume that these networks share similar graphical structures. One such example is gene expression data from different cell types or multiple interventional experiments. To make optimal use of the available data, it is important to develop methods that can jointly estimate the underlying causal networks without learning each network separately. Together with her doctoral student Yuhao Wang and IDSS postdoc Santiago Segarra, Professor Uhler developed algorithms for joint estimation of multiple similar causal networks in high-dimensional settings wherein the number of variables exceeds the number of observations. They are currently validating these algorithms on the problem of learning cell-type-specific gene regulatory networks.

Chromosome Intermingling and Gene Regulation

Gene regulation is inherently linked to the spatial organization of the DNA inside the cell nucleus. In order to understand the mechanisms underlying gene regulation, Professor Uhler's group works toward deciphering the codes that link the packing of the DNA with gene expression. Together with her doctoral student Anastasiya Belyaeva and in collaboration with G. V. Shivashankar's experimental cell biology lab at the National University of Singapore, Professor Uhler developed a network analysis approach for identifying clusters of interactions between chromosomes that the group validated experimentally. Their method integrates one-dimensional features of the genome (e.g., epigenetic marks) with three-dimensional interactions, allowing them to study spatially co-localized regions between chromosomes that are functionally relevant. They observed that clusters of interchromosomal regions fall into active and inactive categories and found that active clusters share transcription factors and are enriched for transcriptional machinery, suggesting that chromosome intermingling regions play a key role in genome regulation. This method provides a unique quantitative framework that can be broadly applied to study the principles of genome organization and regulation during processes such as cell differentiation and reprogramming. This work was published in the *Proceedings of the National Academy of Sciences*.

During the past year, Professor Uhler and her collaborator G. V. Shivashankar were invited to write reviews in prestigious cell biology journals, including *Nature Reviews*, *Cell Biology*, *Trends in Cell Biology*, and *Trends in Cancer*, on the important link between the spatial organization of DNA and gene regulation.

Chromosome Packing and Early Cancer Diagnostics

Current cancer diagnostic practices employ various nuclear morphometric measures. While these measures have allowed accurate late-stage prognosis, early diagnosis is still a major challenge. Recent evidence highlights the importance of alterations in mechanical properties of single cells and their nuclei as critical drivers for the onset of cancer. Together with her master's students Adityanarayanan Radhakrishnan and Ali Soylemezoglu, and in collaboration with G. V. Shivashankar's lab, Professor Uhler developed a method to detect subtle changes in nuclear morphometrics at single-cell resolution by combining fluorescence imaging and deep learning. This assay, which includes a convolutional neural net pipeline applied to single-cell images of DNA stained cell nuclei, allowed them to discriminate between normal and human breast cancer cell lines (fibrocystic and metastatic states) as well as normal and cancer cells with high accuracy. Professor Uhler and her colleagues established the sensitivity of their pipeline by detecting subtle alterations in normal cells subjected to small mechanochemical perturbations that mimic tumor microenvironments and showed that their assay provides interpretable features that could aid pathological inspections.

Kalyan Veeramachaneni

Kalyan Veeramachaneni joined LIDS in 2016 as a principal research scientist. His research group, the Data to AI Lab, develops automation technologies for data science, deriving insights from the huge amount of information produced by contemporary systems and building algorithms that emulate human thought.

Today, the demand for data scientists is growing at an unprecedented rate. To address that need, the research conducted by Veeramachaneni and his team focuses on creating algorithms that emulate thought processes. By studying with and working alongside data scientists as they analyze information in a variety of fields ranging from education to medicine, the Data to AI Lab works toward the broad goal of designing unsupervised computer programs that can perform the same tasks as human data scientists. Concurrent with this research, the group is pursuing the Human-Data Interaction Project, a research venture designed to enable seamless human interaction with these complex and still-developing technologies and to extend the capabilities of human researchers.

In pursuit of these goals, Veeramachaneni, along with his colleagues and students, has developed and released two major software systems aimed at increasing the pool of possible data scientists as well as enhancing the productivity of these individuals.

FeatureHub: Toward Crowdsourcing Data Science

One critical but challenging step in any data science effort is feature engineering, the process in which raw data are transformed into variables ready for inclusion in a machine learning model. In collaboration with his student Micah Smith, Veeramachaneni proposed a new paradigm for feature engineering in a collaborative framework and designed FeatureHub, a software platform on which that paradigm is implemented. On FeatureHub, independent data scientists collaborate on a feature engineering task, viewing and discussing each other's work in real time. Feature engineering source codes created by independent data scientists are then integrated into a single predictive machine learning model. The platform includes an automated search for the best possible machine learning algorithm that delivers an optimized model without requiring any effort. This automation allows users to focus on engineering while still receiving immediate feedback on the performance of features.

This approach can reduce redundancy as well as decrease the amount of time required to complete a particular task. Veeramachaneni and his team tested the efficacy of their platform on two data science problems by soliciting solutions from freelance data scientists. A total of 41 data scientists participated in the experiment, spending 171 hours on the platform and collecting 1,952 features across the two problems. Thirty-two of the participating data scientists successfully submitted at least one feature.

Models derived from this collective work performed comparably with the best models submitted by expert data scientists working for weeks or months at a time in a competitive environment. Although the scores achieved were not close to winning such competitions, they did place our automatically generated models within a few hundredths of a point of the best scores.

Auto-Tune Models

In other work, Veeramachaneni and a team that included Thomas Swearingen and Professor Arun Ross from Michigan State University, student Bennett Cyphers, and former student Will Drevo tackled the problem of machine learning model selection and tuning. They developed a distributed, collaborative, scalable system for automated machine learning called auto-tuned models, or ATM. In this system, data scientists simply upload a data set, choose a subset of modeling methods, and then employ ATM's hybrid Bayesian and multi-armed bandit optimization system. The distributed system quickly delivers results in the form of ready-to-predict models and a variety of metrics—confusion matrices, cross-validation results, and training timings—used to evaluate these models.

Veeramachaneni and his team evaluated the efficacy of ATM using 420 publicly available data sets on which the models were trained for several days. (On the OpenML platform, where these data sets originate, data scientists can download a data set, try different models on their local machines, and upload the results from their trials.) ATM generated the largest repository of trained models; across these 420 data sets, a total of three million models were generated, resulting in approximately four terabytes of models and corresponding performance metrics. Comparisons of the ATM-generated models with the models generated by data scientists showed that ATM performed better than human-generated solutions on 30% of the data sets. For every data set on which ATM outperformed the human-submitted solution, Veeramachaneni and his team calculated the time difference between the first and the best submission made by data scientists to the OpenML platform. On average, the difference was 243 days. A similar calculation revealed that ATM's search can generate a solution that beats the best human solution within a few minutes.

Moe Win

The Wireless Information and Network Sciences Laboratory, led by Professor Moe Win, is involved in multidisciplinary research that encompasses developing fundamental theories, designing cooperative algorithms, and conducting network experiments for a broad range of real-world problems.

To advocate outreach and diversity, the group is committed to attracting graduate and undergraduate students from underrepresented and minority groups and to giving them exposure to theoretical and experimental research at all levels. The group has a strong track record of hosting both UROP students and students from the MIT Summer Research Program. Professor Win maintains dynamic collaborations and partnerships with academia and industry, including the University of Southern California; the University of California, Santa Barbara; Arizona State University; the University of Bologna and the University of Ferrara in Italy; the Vienna University of Technology in Austria; the University of Lund in Sweden; the King Abdullah University of Science and Technology in Saudi Arabia; the Singapore University of Technology and Design and Nanyang Technological University in Singapore; Kyung Hee University in Korea; Draper Laboratory; the Jet Propulsion Laboratory; and the Centre for Maritime Research and Experimentation in Italy.

Current research topics being investigated by Professor Win and his group include network localization and navigation, network interference exploitation, intrinsic wireless secrecy, adaptive diversity techniques, ultra-wide-bandwidth systems, and quantum information science. Details of a few specific projects are provided below.

Network Localization and Navigation

The group has made notable contributions to the field of network localization and navigation, in particular enhancing location secrecy, designing and implementing resource-efficient network localization and navigation algorithms, and developing an approach for multi-target tracking (MTT). The group established a theoretical foundation and developed algorithms for protecting location secrecy. They introduced a location secrecy metric for a general eavesdropper measurement model that accounts for unknown deterministic parameters (e.g., channel conditions, time offset) of the localization process. The expression of the location secrecy metric for typical scenarios was determined. Based on insights gained from that analysis, the group conducted a case study in a wireless localization network and developed an algorithm that diminishes the eavesdropper's capabilities by exploiting the reciprocity of channels. The group is continuing to develop the localization system, called Peregrine. Distributed network localization algorithms based on the spatiotemporal fusion have been implemented in Peregrine, and the group conducted a series of experiments to evaluate the system's performance. Specifically, the localization performance of Peregrine when two agents perform cooperative node inference was compared with the case in which the agents perform noncooperative node inference.

The group has also evaluated the performance of the conic programming-based node prioritization (CPNP) scheme in a network with a single agent. In particular, the localization performance of the CPNP scheme was compared with a uniform allocation scheme. Experimentation results showed the performance improvement of cooperation and node prioritization. In addition, the group has developed a paradigm for scalable MTT that is based on factor graphs and the loopy sum-product algorithm. The approach has advantages in terms of estimation accuracy, computational complexity, and implementation flexibility. Most important, it provides a highly effective, efficient, and scalable solution to the probabilistic data association problem, a major challenge in MTT. The group has evaluated the algorithms using measured data captured by two radar stations with overlapping fields of view observing a large number of targets simultaneously. The group also developed a Bayesian method for joint navigation and

MTT in mobile agent networks wherein joint inference is performed through a factor graph formulation. Performing the sum-product algorithm on the formulated joint factor graph enables a probabilistic information transfer between the navigation and MTT stages that can improve the performance of both stages.

Quantum Information Science

Quantum entanglement serves as a valuable resource for many important quantum operations. In this context, the group devoted its effort to the development of efficient quantum entanglement distillation algorithms. A pair of entangled qubits can be shared between two agents by first preparing a maximally entangled qubit pair at one agent and then sending one of the qubits to the other agent through a quantum channel. In this process, deterioration of entanglement is inevitable since the noise inherent in the channel contaminates the qubit. To address this challenge, various quantum entanglement distillation (QED) algorithms have been developed. Among them, recurrence algorithms have advantages in terms of their ease of implementation and robustness. However, the efficiency of recurrence QED algorithms has not been investigated thoroughly in the literature. The group has put forth two recurrence QED algorithms that adapt to the quantum channel to tackle the efficiency issue. The proposed algorithms have guaranteed convergence for quantum channels with two Kraus operators, including phase-damping and amplitude-damping channels. Analytical results show that the convergence speed of these algorithms is improved from linear to quadratic and that one of the algorithms achieves the optimal speed.

Events and Communications

LIDS continues to organize its signature events: the broadly attended LIDS seminar series and the LIDS student conference, a student-run event that provides an interactive forum for students to discuss their research and features several distinguished plenary speakers each year.

LIDS faculty also continue to be involved in the organization of major workshops and conferences. Two notable examples are as follows:

- The MIT Power Systems Brainstorming Workshop, an informal event organized by Marija Ilic that brought together leading researchers in the area of managing and controlling modern power systems and smart grids
- The NSF Workshop on Low-Latency Wireless Random-Access, hosted by LIDS and organized by Professor Yury Polyanskiy, which focused on new research questions around preparing the next-generation IoT network

In addition, LIDS faculty have been key contributors to the organization of various events under the umbrella of IDSS and the Statistics and Data Science Center (SDSC), which sits within IDSS. These events include the annual Women in Data Science Conference (jointly presented by Harvard and MIT and co-organized by Professor Caroline Uhler); the annual Statistics and Data Science Day, a community-building event for those interested in statistics at MIT; and the weekly LIDS and Stats Teas, which provide students and postdocs an opportunity to give brief research presentations to the community in an informal setting.

Finally, LIDS continues to produce its annual community-oriented magazine, *LIDS|ALL*, which consistently receives great praise. The magazine includes articles on important events related to LIDS and profiles of individuals whose lives have been shaped by the lab.

Awards

LIDS faculty, students, and alumni continue to receive substantial recognition for their contributions, with numerous national and international awards and honors.

Professor Robert Berwick received the EECS Jerome H. Saltzer Award for teaching.

Matthew Brennan, Professor Guy Bresler, and RLE postdoc Wasim Huleihel received a Best Student Paper Award at the 2018 Conference on Learning Theory.

Professor Luca Carlone and his co-authors won the *IEEE Transactions on Robotics* King-Sun Fu Memorial Best Paper Award for "On-Manifold Preintegration for Real-Time Visual-Inertial Odometry."

Wehnhan Dai received the 2017 Marconi Society Paul Baran Young Scholar Award.

Rupamathi Jaddivada was selected for the 2018 cohort of rising stars in EECS. She is supervised by Professor Marija Ilic.

Igor Kadota was presented the Aeronautics and Astronautics Graduate Teaching Assistantship Award, given annually to a graduate student "for conspicuous dedication and skill in helping fulfill a subject's educational objectives."

Professors Sertac Karaman and Eytan Modiano, along with LIDS student Rajat Talak, received the 2018 ACM MobiHoc Best Paper Award for "Optimizing Information Freshness in Wireless Networks under General Interference Constraints."

Professor Eytan Modiano received an MIT Committed to Caring Award in recognition of his outstanding student advising and mentorship. In addition, Professor Modiano and his students Igor Kadota and Abhishek Sinha (now with Qualcomm) won a 2018 INFOCOM Best Paper Award for "Optimizing Age of Information in Wireless Networks with Throughput Constraints."

Antoni Rosinol and his collaborator won the 2018 Siemens AI Hackathon. He is supervised by Professor Carlone.

Professor Devavrat Shah, along with his students Anish Agarwal, Muhammad J. Amjad, and Dennis Shen, received a best poster award at the NIPS Time Series Workshop 2017 for "Time Series Forecasting via Matrix Estimation." Also, Professor Shah won an EECS Frank Quick Faculty Research Innovation Award.

Professor John Tsitsiklis received the 2018 IEEE Control Systems Award. In addition, Professor Tsitsiklis won the Saul Gass Expository Writing Award from Institute for Operations Research and the Management Sciences (INFORMS) and the Ruth and Joel Spira Teaching Award from EECS.

Professor Moe Win received several best paper awards: the Best Scientific Contribution at the 2017 IEEE International Symposium on Wireless Communication System (with co-authors Giovanni Chisci, Hesham ElSawy, Andrea Conti, and Mohamed-Slim Alouini), the Best Paper Award at the 2017 IEEE Latin-American Conference on Communications (with co-authors Bryan Teague, Zhenyu Liu, and Florian Meyer), and the Marconi-BISITE Best Paper Award at the 2017 IEEE International Conference on Ubiquitous Wireless Broadband (with co-authors Wenhan Dai and William C. Lindsey).

Honors

Professor Audun Botterud gave a keynote presentation ("Electricity Market Design with Variable Renewable Generation: A U.S. Perspective") during a plenary session at the 15th International Association for Energy Economics European Conference in Vienna, Austria.

Professor Munther Dahleh was a plenary speaker at multiple workshops, including an NSF workshop on online learning of dynamic data.

Professor Jonathan How was named an IEEE Fellow for his extraordinary research contributions to guidance and control of air and space vehicles.

Professor Eytan Modiano was inducted into the University of Connecticut Academy of Distinguished Engineers.

Professor Asuman Ozdaglar was named head of the Department of Electrical Engineering and Computer Science effective January 1, 2018.

Professor Pablo Parrilo was named a 2018 SIAM (Society for Industrial and Applied Mathematics) Fellow in recognition of his "foundational contributions to algebraic methods in optimization and engineering."

Professor Yury Polyanskiy was granted tenure by the Department of Electrical Engineering and Computer Science.

Professor John Tsitsiklis received an honorary doctorate from the Athens University of Economics and Business.

Professor Caroline Uhler was promoted to associate professor without tenure in the Department of Electrical Engineering and Computer Science effective July 1, 2018.

Organization

Professor John Tsitsiklis continues to serve as LIDS director (having started in this role in April 2017). Professor Eytan Modiano joined as associate director effective July 1, 2017. On the occasion of this leadership change, a comprehensive review of all aspects of the lab was initiated, including systematic collection of opinions and input from the entire community of faculty, research and administrative staff, and students. This process led to a number of new initiatives aimed at improving intellectual and social life within the lab; examples include mentoring events, student-led events, and efforts to connect with the LIDS alumni community.

AY2018 Key Statistics

Faculty PIs: 25

Research staff PIs: 4

Affiliate members: 7

Administration, technical, and support staff: 10

Postdocs and other research staff (non-PIs): 26

Visitors and other affiliates: 38

Graduate students: 115

Visiting students: 11

Overall Outlook

LIDS is a world-leading center for fundamental research in the information and decision sciences. It occupies a unique niche at the interface of theory and applications in diverse areas and is a central component underlying many recent technological advances and challenges, including in the currently vibrant fields of data science, statistics, machine learning, and intelligent systems. There are of course many activities in these domains taking place outside LIDS, including prominent applications. Within this broad range of activities, LIDS serves as a focal point in the development of the underlying fundamental methodologies and as a meeting ground for like-minded researchers.

In addition to fundamental research, LIDS is engaged in furthering collaborative efforts that balance theory and practice for maximal impact. The umbrella provided by IDSS and the resulting opportunities for cross-cutting collaborations are very helpful in this respect.

Finally, while LIDS is a research-oriented entity, the lab's faculty maintain a leading role in curriculum innovation, thus bridging research and the classroom in areas such as data science, control and autonomy, and networks.

John Tsitsiklis
Director
Clarence J. Lebel Professor, Department of Electrical Engineering and Computer Science

Eytan Modiano
Associate Director
Professor, Department of Aeronautics and Astronautics