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 is one of the core research laboratories in the Schwarzman College of Computing. 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. LIDS is the longest continuously operating laboratory at MIT. In 2019, the laboratory celebrated its 80th anniversary.

Participants and Collaborations

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

LIDS has a close relationship with the Institute for Data, Systems, and Society (IDSS), which in addition to advancing disciplinary methodologies in statistics, data science, and information and decision systems, nurtures cross-cutting connections, especially with the social sciences, in order to address complex societal challenges. LIDS was instrumental in the launch of IDSS and LIDS faculty play a pivotal role in defining the IDSS intellectual agenda—leading efforts in statistics and around 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 being heavily involved in the search for new faculty in the fields of networks and statistics. In particular, LIDS faculty have played a central role in launching the IDSS MicroMasters in Statistics and Data Science.

LIDS researchers continue to have great success in obtaining funding for our broad and deep research agenda, and continue to develop relationships with industrial organizations and national laboratories including Lincoln Laboratory (LL), NASA Jet Propulsion Laboratory, Ford Motor Company, MIT-IBM Watson AI Lab, IBM, SES S.A., Liberty Mutual Insurance Company, Lockheed Martin Corporation, Anheuser-Busch, Los Alamos National Security, Motional, 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 also a continuous stream of world-leading researchers as visitors and collaborators.

LIDS has been strengthened this year with the addition of new EECS faculty member, Assistant Professor Ashia Wilson. Her research activities center on optimization, with an emphasis on the context of learning algorithms, and broadened to related areas such as statistical inference and fairness. In addition, Professor David Simchi-Levi, a faculty member in CEE, joined LIDS as a principal investigator (PI) this year. His research interests cover transportation and logistics, supply chain management, revenue and yield management, and risk management, with an emphasis on analytical methods.

Last year, LIDS redefined the role of LIDS Affiliate Members, fostering stronger ties with a number of MIT faculty who, although not LIDS PIs, are intellectually aligned with the lab's research agenda and are engaged in substantial interactions. The current list of affiliate members is comprised of Professors Anant Agarwal (EECS), Hamsa Balakrishnan (AeroAstro), Tamara Broderick (EECS), David Gamarnik (Sloan), Jongyoon Han (EECS), Stefanie Sabrina Jegelka (EECS), and Youssef M. Marzouk (AeroAstro), as well as Senior Research Scientist Anuradha M. Annaswamy (MechE).

The already strong core of existing LIDS PIs, together with the extended community of Affiliate Members, have turned LIDS into a preeminent entity—both within MIT and more broadly in the academic world—in the fields of data science and the foundations of machine learning. Over the past few years, with the addition of faculty members from AeroAstro and CEE, LIDS has also developed a core expertise in autonomy algorithms and autonomous vehicles. At the same time, traditional LIDS core areas—communications, information theory, networks, optimization, and control—remain active and strong.

Joining the Stephen A. Schwarzman College of Computing

LIDS officially joined the newly formed Schwarzman College of Computing in January 2020 as one of its research units. The intellectual mission of LIDS, with its emphasis on information, data, and decision making, falls squarely within the center of gravity of the college, and LIDS faculty are actively engaged in cross-cutting initiatives taking place there.

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, or 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, often associated with the legacy of Wiener and

Shannon, 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 select application domains that, in a virtuous cycle, also provide inspiration for further methodological research.

To achieve these aims, LIDS research is underpinned by:

- A set of core mathematical disciplines, including probability and statistics; dynamical systems; optimization and decision theory
- A set of core engineering disciplines, including inference, statistical data processing, data science, and machine learning; transmission of information; networks; 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 leads 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 development of large-scale data processing software systems. Research ranges from 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

This area aims 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, methods that exploit the algebraic structure of large-scale problems, as well as simulation-based methods are also studied.

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, 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, the design of optimal resource allocation schemes for wireless networks, and the design of optimal architectures and control algorithms for data centers and cloud networks. Additional recent directions include the analysis 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 and 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, as well as issues of scalability, robustness, and performance limits.

Some particular areas of significant recent activity that we wish to highlight include the following:

- 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
- Social network analysis and characterization
- Network navigation and localization
- Transportation network analysis, control, and design
- Ultra-wideband and other emerging communications technologies

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 research 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, and the design of efficiently computable incentive methods for large-scale, networked, dynamic environments
- New frameworks for modelling 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—a general and rich framework for high dimensional inference
- Development of causal inference methods for gene regulation and early disease diagnostics

Research Highlights

Professor Saurabh Amin made advances in the study of mixed-traffic involving connected and automated vehicles as well as human-driven ones.

Professor Dimitri Bertsekas has updated his recent research monograph on "Rollout, Policy Iteration, and Distributed Reinforcement Learning" with a comprehensive analysis of multi-agent problems and their online versions.

Professor Robert C. Berwick made significant advances in understanding the limitations of deep neural networks applied to processing language.

Audun Botterud published a key paper on the value of transmission in decarbonizing the US electricity system, illustrating the importance of inter-regional planning and coordination in meeting the US administration's ambitious decarbonization goals.

Professor Guy Bresler and his collaborators have made major new advances in their theory for the limitations of some of the widely utilized algorithms for high-dimensional statistical problems.

Professor Luca Carlone and his group have continued their development of certifiable perception algorithms with provable guarantees on robustness and efficiency.

Professor Munther Dahleh and his group have developed a first-of-its-kind cross-domain open-access data hub, integrating data from across all existing US wholesale electricity markets with Covid-19 cases, weather, mobile device location, and satellite imaging data.

Professor Jonathan P. How developed new multi-agent reinforcement learning algorithms that are adaptable across the full spectrum of competitive, mixed-incentive, and cooperative domains.

Marija Ilic led a Lincoln Laboratory team that completed a key study on demand-side integration in electricity grid service for the Advanced Research Projects Agency-Energy (ARPA-E).

Professor Ali Jadbabaie and his group continued their work on the study of misinformation spreading in social networks.

Professor Patrick Jaillet continued his work on online optimization and learning.

Professor Sertac Karaman has developed novel algorithms for joint perception and decision-making for autonomous vehicles; he has developed the foundations for two ventures while on sabbatical from MIT.

Professor Alexandre Megretski made key contributions towards the design of adaptive controllers that uphold the certainty equivalence principle, which is a key concept in the design of control systems.

Professor Sanjoy K. Mitter has published a key commentary that addresses infrastructure challenges towards the decarbonization of the electricity grid.

Professor Eytan H. Modiano has widened his foundational study of networks towards networks autonomous vehicles using new testbeds.

Professor Asuman E. Ozdaglar and her group developed robust adversarial machine learning algorithms; in addition, motivated by the Covid-19 pandemic, they studied optimal adaptive testing that combines different types of tests with voluntary social distancing.

Professor Pablo A. Parrilo continued his work on algorithms for solving large-scale complex optimization problems and their connections to algebraic geometry.

Professor Yury Polyanskiy developed a new theory for entropy estimation, which has a number of applications including estimating information flows in deep neural networks.

Professor Alexandre Rakhlin and his group made significant advances in our understanding of the performance of overparameterized statistical learning algorithms.

Mardavij Roozbehani made significant advances in understanding the impact of machine learning in farming, focusing on the effects of external shocks such as adverse weather.

Professor Devavrat Shah and his group continued the development of their tensor estimation methods for enabling causal inference through machine learning and their applications in "what if analysis" tools for policy evaluation, including the Covid-19 pandemic and personalized medicine.

Professor David Simchi-Levi continued the development of analytical techniques and algorithmic tools for decision making in problems that involve significant amount of uncertainty.

Professor Suvrit Sra and his group made significant advances in our understanding of stochastic gradient descent algorithms used in neural network training, developing tight bounds on computational complexity for the first time.

Professor John N. Tsitsiklis served as the director of LIDS until December 31st, 2020, and subsequently started his sabbatical leave exploring the foundations of reinforcement learning, where he made seminal contributions 20 years ago.

Professor Caroline Uhler applied new machine learning methods that were developed to tackle the problem of drug repurposing and joint imaging-and-sequencing of cells.

Kalyan Veeramachaneni and his group developed a new open-source end-to-end automated machine learning framework for creating predictive models for health care data.

Professor Ashia Wilson is working on fairness in machine learning, most recently applied to health inequity in organ donation using data from organ procurement organizations.

Professor Moe Win developed a new paradigm for scalable multi-object tracking and continued their work in the area of quantum information science.

Professor Cathy Wu developed new machine learning algorithms that solves large-scale optimization problems for vehicle routing by delegating smaller scale problems to other solvers.

Faculty Activities

The activities listed below are organized in terms of individual faculty. Nevertheless, many of the major research activities not only cut across the disciplines, applications, and emerging areas mentioned previously, but are also collaborative with others within LIDS and elsewhere at MIT.

Saurabh Amin

The Resilient Infrastructure Networks group lead by Associate Professor Saurabh Amin is pursuing research in the design of control of infrastructure systems, using game theory, stochastic control, and optimization in networks. Main areas include resilient network control, information systems and incentive design, and optimal resource allocation.

By focusing on important questions in the domains of transportation, electric power, and urban water networks, Amin develops new theory and tools for improving the performance of these systems in the face of disruptions, both stochastic and adversarial.

The research on resilient network control aims to design operational strategies that maintain system performance under variety of disturbances. Recent work focuses on the robustness of highway traffic operations, such as effects of incidents on the stability of traffic queues, and system throughput in mixed-traffic highways with platoons of connected and autonomous vehicles (CAVs). Amin's group develops a new approach to control the macroscopic interactions between CAVs and normal traffic.

The work on information systems and incentive design examines the effects of heterogeneities in information access and agents' strategic behavior on the equilibrium outcomes in multi-agent systems. Amin's group studies stochastic learning dynamics in which strategic agents repeatedly adjust their strategies in a game while learning an unknown payoff-relevant parameter. The key aspect is feedback between the agents' strategy updates and their belief updates, which impacts the long-run outcomes. They provide first results on convergence and stability analysis for this general model. Another ongoing work pursues incentive design for carpooling and road tolling in CAV-supported mobility systems with the goal of improving the societal welfare.

The research on optimal resource allocation has investigated the use of microgrid technology and allocation of low-inertia distributed energy resources to improve resilience of electricity distribution networks against correlated failures. This work involves developing scalable algorithms for multi-stage stochastic optimization problems with mixed-integer constraints and enables quantitative evaluation of resiliency improvement through optimal allocation decisions.

Dimitri Bertsekas

Dimitri P. Bertsekas, Jerry McAfee (1940) Professor Post-Tenure, performs research on problems of sequential decision making under uncertainty, which are pervasive in communication networks, manufacturing systems, and logistics, and in the 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. In the preceding year, he updated his recent research monograph "Rollout, Policy Iteration, and Distributed Reinforcement", published by Athena Scientific, which aims to clarify the uses of distributed computation in Reinforcement Learning in the context of the rollout and policy iteration methods, and incorporates Bertsekas' latest research. Major updates and related research include a comprehensive analysis of rollout and policy iteration algorithms for multiagent problems, their on-line versions, and related research on multistage zero-sum games.

Robert C. Berwick

During the past year, Berwick's research group uncovered new and critically important weaknesses in the currently popular "deep neural networks" used to process human language. The group also found an intuitive way to think about deep neural networks, so it is easy to understand why they work well much of the time, but then fail on examples that children never get wrong. The group found the weaknesses by assembling a comprehensive database of 2,400 kinds of contrasting examples that linguists use to build theories of human language. These examples have been vetted statistically by using human subjects, so these examples serve as a "gold standard" for evaluation. They found deep neural network systems only get about 30% of such examples correct, far lower than the networks' performance as reported elsewhere. The reason is that our database sentences probe many different areas of language knowledge, as opposed to "sentences in the wild" that are likely to be highly repetitive, but all similar. Neural networks thus memorize repetitions but cannot match the fully creative nature of human language. This result can be summarized as the networks "memorize, but do not generalize," since this was not an expected result given the highly publicized success of such networks. The group's second more intuitive and theoretical result explains why networks just memorize. One can think of such networks as a mesh of many, many slightly bendable lines or tiles (formally, splines) that are woven together to pass through all the training data, "flying over" the data and hitting each training point like a rug with many nearly flat ripples. But this means the network cannot respond well to new examples, generalizations, the rug cannot "bend" to cover them. They do not generalize the way children do, a critical gap that remains to be filled.

Audun Botterud

Audun Botterud has been a principal research scientist in LIDS since September 2016. He is also a research affiliate in MIT's Energy Initiative (MITEI) and Center for Energy and Environmental Policy Research, and he holds a co-appointment at Argonne National Laboratory. The main goal of Botterud's research is to improve the understanding of the complex interactions between engineering, economics, and policy in electricity markets, and ultimately enable the transition towards 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.

Botterud's research currently focuses on three main application areas, with recent highlights briefly outlined below:

1. Electricity markets: A project team lead by former LIDS visiting professor Alberto Lamadrid (Lehigh University) with several LIDS contributors—Audun Botterud, Marija Ilic, Patrick Jaillet, and Stefanos Delikaraoglou—launched a new ARPA-E project on improved risk management for electricity markets with increasing shares of variable renewable energy. The MIT team is developing a novel market-clearing formulation that better accounts for uncertainty while still maintaining the basic properties of current market clearing process.

2. Decarbonization of energy systems: Botterud and colleagues published a seminal paper in *Joule* on the value of transmission in decarbonizing the US electricity system, illustrating the importance of inter-regional planning and coordination in meeting the US administration's ambitious decarbonization goals (with Patrick Brown, MITEI).

3. Energy storage analytics: Botterud and colleagues have expanded their work on improved representation of energy storage in power system optimization models, with a particular focus on how to best account for battery degradation in generation expansion planning (with Mehdi Jafari, LIDS, Apurba Sakti, MITEI).

Guy Bresler

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

In joint work with student Enric Boix and Frederic Koehler, Bresler continued his line of work on learning graphical models in the data-poor regime where the structure itself cannot be recovered. In this latest paper they considered the problem of learning a tree-structured Ising model from data, such that subsequent predictions computed using the model are accurate. Concretely, the aim is to learn a model such that posteriors P(Xi|XS) for small sets of variables S are accurate. The new paper introduces an algorithm that carefully combines elements of the Chow-Liu algorithm with tree metric reconstruction methods to efficiently and optimally learn tree Ising models under a prediction-centric loss. In contrast, it is shown that the celebrated Chow-Liu algorithm can be arbitrarily suboptimal.

Researchers currently use a number of approaches to predict and substantiate information-computation gaps in high-dimensional statistical estimation problems. A prominent approach is to characterize the limits of restricted models of computation. In joint work with student Matthew Brennan as well as Samuel Hopkins, Jerry Li, and Tselil Schramm, Bresler studied two of the most popular restricted computational models—the statistical query framework and low-degree polynomials—in the context of high-dimensional hypothesis testing. The main result is that under mild conditions on the testing problem, the two classes of algorithms are essentially equivalent in power. Corollaries included new statistical query lower bounds for sparse PCA, tensor PCA and several variants of the planted clique problem.

In joint work with student Brice Huang, Bresler aimed to better understand how qualitative properties of the energy landscape of solutions of a problem can be used to determine success or failure of classes of algorithms. In their paper they studied the random k-SAT problem, the average-case version of the canonical NP-complete problem, and determined the precise threshold (up to constant factor) for the number of clauses versus variables at which low-degree polynomial algorithms can or cannot find a solution. This shows the first sharp computational phase transition of random k-SAT for a class of algorithms. The proof establishes and leverages a new many-way overlap gap property (OGP) tailored to random k-SAT, overcoming several barriers to progress limiting the reach of prior OGP methodology and furthering the connection with heuristics from mathematical physics.

Luca Carlone

Professor Carlone is the director of the Sensing, Perception, Autonomy, and Robot Kinetics (SPARK) group. The mission of his group is to develop theoretical understanding and practical algorithms for robust and efficient *robot perception*. For an autonomous vehicle (e.g., a drone or a self-driving car), perception is the problem of creating an internal model of its surroundings using sensor data and prior knowledge. Despite recent advances in robot perception, both researchers and practitioners are well aware of the brittleness of current perception systems, and a large gap still separates robot and human perception. The SPARK group is working on bridging this gap by investigating two fundamental topics—the design of certifiable perception algorithms for high-integrity autonomous systems, and the development of algorithms and systems for real-time 3D scene understanding.

During this reporting period, the group has made substantial progress on the design of certifiable algorithms by providing a general theory for optimality certification in geometric perception problems; developing fast solvers that can check optimality or correct suboptimal estimates; and extending the reach of certifiable algorithms to category-level perception problems. This effort has been recognized with an National Science Foundation (NSF) Career Award, a 2020 Honorable Mention from the IEEE Robotics and Automation Letters, and a best paper finalist certificate at the "Robotics: Science and Systems" conference in 2021. One of the algorithms developed by the SPARK group is now included in MATLAB's Navigation Toolbox. Regarding the second research topic, real-time 3D scene understanding, the group has established a collaboration with Professor Jonathan How's group to demonstrate large-scale metric-semantic mapping in multi-robot systems within the Army Research Laboratory Distributed and Collaborative Intelligent Systems and Technology (DCIST) program, extending the group's previous work on *Kimera*, an open-source library for real-time metric-semantic mapping. As further recognitions, the SPARK group have received a Track Best Paper Award at the IEEE Aerospace Conference; and Carlone was promoted to associate professor without tenure by AeroAstro.

Munther Dahleh

Munther Dahleh, director of IDSS and the William A. Coolidge Professor of EECS, focused his research on advancing problems in machine learning for controlled dynamical systems with application in neural learning and control.

Towards Data Auctions with Externalities

Dahleh's group demonstrates that the presence of externalities increases the optimal revenue of a monopolistic data seller by letting firms pay to prevent allocations to other competing firms. This is shown by first reducing the combinatorial problem of allocating and pricing multiple datasets to the auction of a single digital good. Then, they find the welfare and revenue maximizing mechanisms, highlighting how the forms of firms' private information affects their overall structures.

Toward Carbon-neutral Electricity and Mobility: Is the Grid Infrastructure Ready?

A joint op-ed with S. Mitter, C. Singh, L. Xie, and S. Oren summarizes key challenges and opportunities in the electric grid sector as the world makes an ambitious transition toward carbon neutrality. How to design a coordinated incentive and operational architecture between these, the electricity and transportation sectors remains a key intellectual challenge for the research and policymaking communities.

Data-driven Control of Micro-climate in Buildings: An Event-triggered Reinforcement Learning Approach

A key challenge for smart buildings is learning a good control policy in a short period of time in an online and continuing fashion. To tackle this challenge, an event-triggered paradigm, as opposed to classic time-triggered, is proposed in which learning and control decisions are made when events occur, and enough information is collected. Using extended policy gradient theorems and temporal difference methods in a reinforcement learning set-up, Dahleh and colleagues propose two learning algorithms for event-triggered control of micro-climate in buildings.

A Cross-Domain Approach to Analyzing the Short-Run Impact of Covid-19 on the US Electricity Sector

Dahleh and colleagues release a first-of-its-kind cross-domain open-access data hub, integrating data from across all existing US wholesale electricity markets with Covid-19 cases, weather, mobile device location, and satellite imaging data. Leveraging cross-domain insights from public health and mobility data, they rigorously uncover a significant reduction in electricity consumption that is strongly correlated with the number of Covid-19 cases, degree of social distancing, and level of commercial activity.

Jonathan How

Jonathan How leads research efforts focused on the control of multiple autonomous agents, with an emphasis on distributed decision making with uncertainty; path planning, activity, and task assignment; mission planning for unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs); sensor network design; and robust, adaptive, and nonlinear control. Professor How is also the principal investigator of the Aerospace Control Laboratory (ACL). A key aspect of ACL is RAVEN (Real-time indoor Autonomous Vehicle test Environment), a unique experimental facility that uses a motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and aircraft, and robust coordination algorithms for multiple vehicles; and ground projection system that enables real-time animation of the planning environment, beliefs, uncertainties, intentions of the vehicles, predicted behaviors (e.g., trajectories), and confidence intervals of the learning algorithms. Major research accomplishments in this fiscal year are in the general areas of localization and mapping, planning and navigation, and multiagent reinforcement learning.

Localization and Mapping

ACL researchers developed an algorithmic solution that correctly identifies data that must be fused during collaborative mapping even when 99% of the input is outliers.

The algorithm has superior computational efficiency and accuracy compared to state-of-the-art solutions. The second research thread was on accurate collaborative localization and mapping by robot teams. This goal relies on efficient decentralized optimization. ACL researchers developed efficient distributed manifold optimization techniques that provide global optimality guarantees and support asynchronous communication. The algorithm achieved state-of-the-art speed and accuracy, and was demonstrated through real-world multi-robot localization and mapping systems.

Planning and Navigation

ACL researchers developed a path planning algorithm that can generate collision-free trajectories in a completely decentralized and asynchronous way. Moreover, perception-awareness allows these drones to maximize the information gained about the environment. Extensive simulations have proven the superiority of these algorithms with respect to state-of-the-art solutions, and hardware experiments have shown its applicability to fast, real-world flights.

Multiagent Reinforcement Learning

ACL researchers developed a principled method that considers non-stationary policy dynamics of all agents in the environment to adapt efficiently to other agents' changing behaviors. The method was evaluated on a diverse suite of multiagent benchmarks and demonstrated the adaptation ability across the full spectrum of mixed incentive, competitive, and cooperative domains.

Marija Ilic

Marija Ilic (Professor Emerita, Carnegie Mellon University) is a senior research scientist at LIDS and a permanent senior staff member at Lincoln Laboratory. She is also affiliated with IDSS. This year, Ilic has been working on several different collaborative research projects. These include serving as MIT co-PI on Texas A&M University-led Department of Energy project on Cyber-Secure Microgrids; MIT investigator on Lehigh University-led ARPA-E project concerning market derivatives for risk management in electric energy systems; technical lead on MIT LL Office of Naval Research (ONR) project on Reconfigurable Microgrids; PI on MIT Portugal collaborative project on use of software to manage renewable resources; PI on Early-concept Grants for Exploratory Research NSF project concerning fundamental principles of modeling, simulations and control for the changing electric energy systems. In addition, Ilic and colleagues also completed an MIT LL ARPA-E project concerning demand side integration in electricity grid service.

Ilic Supervised and graduated three EECS doctoral students and two master's students this academic year and is in the process of growing her group. Over the summer she offered the EdX course *Principles of Modeling, Simulations, and Control for Electric Energy Systems* which had over 2,000 listeners.

Ilic also gave invited keynote talks and lectures over the course of the year: Energy Systems Innovation Center, Washington State University; ARPA-Engineering Microgrids with Control Co-Design Workshop, University of Toronto; Lunar Surface Innovation Consortium, Johns Hopkins Applied Physics Laboratory; ISPEC2020 Chengdu, Sichuan, China; MITBeaverworks Summer Institute 2021; Federal Energy Regulatory Commission Technical Conference on Increasing Market and Planning Efficiency through Improved Software 2021; Invited Distinguished Lecture in Energy and Earth Distinguished Lecture Series, Sandia National Laboratories; NASA MUREP-Space Technology Artemis Research at Florida International University; Summer School IGEE Canada.

Ali Jadbabaie

During AY2021, Ali Jadbabaie started a new ONR program, jointly with LIDS PI Alexander Rakhlin. This work has led to a series of new results on unraveling the mysteries of deep learning and building stronger ties between optimization and statistical learning theory.

Jadbabaie co-organized with Pablo Parrilo, LIDS PI, the third workshop on Learning for Dynamics and Control (L4DC 2020) which was held virtually on Zoom and was attended by more than 6,300 people worldwide.

Jadbabaie, Amir Ajorlou (research scientist, LIDS), Chin-Chia Hsu (PhD student, Social Engineering Systems [SES]), and Muhamet Yildiz (professor of Economics), submitted a series of new papers on misinformation spreading in social networks to *Review of Economic Studies*.

Jadbabaie and Ozdaglar were recipients of an extension of an IBM grant for research at interface of machine learning and optimization theory.

Throughout 2020 and 2021, Jadbabaie and his students have been an active member of the IDSS Covid-19 Collaboration, dubbed Isolat group, on modelling, intervention, control, and policy evaluation for the Covid-19 pandemic. In particular, SES PhD student Arnab Sarker, Jadbabaie, and Devavrat Shah have created a prediction model for the spread of Covid-19 and have identified new implicit feedback policies implemented by the population in different states. SES PhD student Paolo Bertolotti's work on pool-testing has been extended to networks, creating large savings on testing.

Patrick Jaillet

Patrick Jaillet is the Dugald C. Jackson Professor and is a co-director of the Operations Research Center (ORC). His research focuses on online optimization and learning; machine learning; and decision making under uncertainty. Examples include online and dynamic versions of assignment/matching problems, secretary problems, routing problems, and their generalizations. The research deals with provable results—algorithmic design and analysis—on how to solve such problems under uncertainty, with or without explicit stochastic modeling of the uncertainty. Methodological tools include those from online optimization (competitive analysis), stochastic optimization (robust analysis), online learning (min-max regret analysis, Bayesian updates), reinforcement learning, game theoretic concepts (price of anarchy) and their integrations.

Motivating applications arise from modern transportation sharing systems, dynamic resource allocation problems in various applications arising from the digital economy (search engines and online auctions) and social interactions (job search, house exchanges).

Jaillet's research group at MIT this past academic year has included six PhD students from the ORC—Moise Blanchard, Samuel Gilmour, Gauthier Guinet, Victor Gonzales, Jason Liang, and Sohil Shah—and one SM student from the ORC—Matthew Yuan. His research group in Singapore has included one postdoctoral researcher—Chungling Luo, Singapore-MIT Alliance for Research and Technology Centre (SMART)—and seven PhD students—Zhongxiang Dai, Chi Lam, Rachel Sim, and Haibin Yu, National University of Singapore; Anatoliy Prokhorchuk, Nanyang Technological University; Meghna Lowalekar, Singapore Management University; and Gary Goh, Singapore University of Technology and Design.

Funded research programs over this past academic year came from ONR (Online Optimization and Learning in a Complex Environment); Air Force Office of Scientific Research (Building Attack Resilience into Complex Networks: Deterrence, Inspection, and Recovery); SMART (Future Mobility); MIT-IBM (On-Device Personalization with Meta Learning); and Defence Science and Technology Agency (Online Learning and Decision Making under Uncertainty in Complex Environments).

Sertac Karaman

Sertac Karaman has spent the previous academic year on sabbatical, where he laid foundations for two new ventures. First is a for-profit company that operates in the aerospace and defense domain, licensing intellectual property from MIT. Second is a not-for-profit venture that focuses on broadening education in artificial intelligence (AI) through accessible platforms for learning.

On MIT research, Karaman and his group continued his research on the following fronts:

- Foundations on computing for high-dimensional decision making
- Foundations and applications of fast and agile autonomous vehicles
- Foundations and applications of miniature autonomous vehicles

Regarding the foundations of high-dimensional decision making, the group's most recent publication that extends computing with compressed tensor to hierarchical tensor has appeared in the *Society for Industrial and Applied Mathematics Journal on Matrix Analysis and Applications*. This new publication lays the foundations for handling data that is hierarchically organized, and demonstrates an order-of-magnitude savings when compared to state-of-the-art methods in widely utilized data sets.

Regarding the foundations and applications of fast and agile autonomous vehicles, the group's most recent publication showcases learning fast and agile trajectories using multi-fidelity simulation and experimentation and has appeared in the *International Journal of Robotics Research*. This publication shows that fast and agile trajectories can be learned by leveraging a wide variety of simulations (with ranging fidelity) as well as real experiments. The group showcased substantial increase in performance and provide a path to beat humans in the challenging game of drone racing.

Regarding the foundations and applications of miniature autonomous vehicles, Professor Karaman has grown his joint research group with Vivienne Sze (EECS). The joint group's most recent publication, which will appear at a robotics conference, demonstrates a new hardware implementation of mutual information computation that now achieves seven orders of magnitude higher throughput implemented on an FPGA, when compared to state-of-the-art approximation methods that are designed for and implemented on a CPU.

Alexandre Megretski

Alexandre Megretski works on problems associated with analysis and design of non-linear dynamical systems. Specific areas of interest include design and certification of dynamical strategies in the presence of vision-based feedback, upper and lower bounds of performance of online learning algorithms in dynamical feedback loops, and optimization of signal processing systems used in digital communications. In particular, this year he was able to establish, for the first time in the literature, up-to-a-constant degree of suboptimality of the so-called "certainty equivalence" adaptive controller, applied to a first order system with an uncertain pole location, combined with an induced norm-bounded unmodeled dynamics uncertainty. The suboptimality is given in terms of the "L2 norm," which, for an input–output model, describes the worst-case energy gain.

Sanjoy Mitter

Toward Carbon-neutral Electricity and Mobility: Is the Grid Infrastructure Ready?

The electric power and transportation sectors are the two largest contributors to greenhouse gas emissions in the US and in most other nations. A critical path toward carbon neutrality relies on decarbonizing electric power generation and simultaneously electrifying a major portion of the transportation sector. If successful, this path will fundamentally change the way energy is converted, delivered, and utilized for a sustainable society. Sanjoy Mitter, together with C. Singh, M. Dahleh, L. Xie, and S. Oren, published a commentary piece that takes an ''electric grid-centric'' viewpoint to directly address infrastructure changes that have long lead times and often pose public acceptance issues. A key challenge in the ambitious carbon neutral transition lies in the scale and speed of accomplishing this transformation. They addressed the following questions that underpin this global endeavor to grapple with climate change. Is today's electric infrastructure ready to facilitate such an ambitious decarbonization effort? If not, how should investments be prioritized to leverage feedback from vehicle electrification and further expand the electric infrastructure? This piece summarizes key challenges and opportunities in the electric grid sector as they make an ambitious transition toward carbon neutrality. They argue that there exists a feedback loop between the electricity and transportation sectors. Whereas the electricity sector should plan for an aggressive electrified charging demand from the transportation sector, mobile batteries in cars can also be viewed as an important resource of energy during times of stressed grid conditions. How to design a coordinated incentive and operational architecture between these two sectors remains a key intellectual challenge for the research and policymaking communities. The commentary appeared in *Joule*, 2021.

Eytan Modiano

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

Application domains such as autonomous vehicles, command and control systems, virtual reality, and sensor networks, heavily rely upon the distribution of time-critical information. Over the past few years, CNRG has been developing network algorithms for optimizing information freshness in wireless networks. Moreover, recently the group developed a wireless networking testbed consisting of fully programmable radios. This testbed is being used to experiment and validate network control algorithms for optimizing information freshness. In particular, this past year the group used programmable radios to implement WiFresh, a novel medium access control protocol for maintaining information freshness among network nodes. Additionally, the group applied this WiFresh implementation to a number of application scenarios in the area of robotics and autonomous vehicles.

The group continues to develop learning-based algorithms for network control. In particular, the need for learning arises in networks with a mix of controllable and uncontrollable nodes, where the actions of the uncontrollable nodes can only be observed via feedback. Reinforcement learning can thus be used to make decisions at the controllable nodes, based on such feedback, in order to optimize overall network performance. In particular, the group developed a novel control algorithm, called Tracking MaxWeight, that combines techniques from learning with Lyapunov optimization to help control a network with a mix of controllable and uncontrollable nodes.

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

Asuman Ozdaglar is the Mathworks Professor of EECS. She is also the department head of EECS and deputy dean of academics for the Schwarzman College of Computing. Her research focuses on developing new models, mathematical tools, and algorithms for the analysis and optimization of multi-agent dynamic networks (including technological, social, and economic networks) and new models and algorithms for machine learning (ML).

Her group is currently working on new problem formulations, methods and efficient algorithms for robust machine learning that maintain performance in the presence of perturbations and are capable of adapting to variations in data collection, task objectives, and domain shifts. One of the group's goals is to develop ML models that are robust to various perturbations and generative models, primarily generative adversarial network (GAN) formulations, that can be efficiently trained and generalize well to unseen problem instances. This year the group continued their work on developing efficient algorithms for minmax problems and expanded it in the following dimensions: generalization analysis of minmax learners, personalized decentralized federated learning, stable GAN training, last iterate convergence of minmax algorithms, optimal algorithms for stochastic minmax problems, robust distributed optimization.

Another line of works study algorithms for meta-learning—in recent work, they extend Model-Agnositc Meta-Learning (MAML) for reinforcement learning problems and investigate its generalization properties using algorithmic stability framework. Other recent work aims to understand how simple algorithms can reach approximate optimal points for problems with special structure. The group has also developed new tools for studying game theoretic interactions over large networks. In various projects, Ozdaglar and her group also study questions of data ownership, privacy and data markets, designing review systems for online markets, behavior manipulation using user data by online platforms, spread of misinformation and effects of platform interventions (e.g., effects of algorithms that create filter bubbles on misinformation).

Motivated by the Covid-19 pandemic, the group has also worked on a number of projects that developed models of the spread of the epidemic and designed non-pharmacological interventions for its containment (testing, isolation and lockdown policies).

Pablo A. Parrilo

Pablo Parrilo's research group is focused on mathematical optimization, systems theory, and control, with emphasis on development and application of computational tools based on convex optimization and algorithmic algebra.

Yury Polyanskiy

Yury Polyanskiy conducts research in the areas of mathematics of information (information theory), coding theory, and theory of random processes. His current work focuses on non-asymptotic characterization of the performance limits of communication systems, information-theoretic methods in statistics and machine learning, fault-tolerant circuits and probabilistic methods in combinatorics.

Convergence of Smoothed Empirical Measures with Applications to Entropy Estimation

This paper studies convergence of empirical measures smoothed by a Gaussian kernel. Polyasnkiy and colleagues examine the convergence in terms of the Wasserstein distance, total variation (TV), Kullback-Leibler (KL) divergence, and χ2- divergence. It is shown that regularizing the effect of noise dramatically changes the convergence rate of empirical measures, making it 1/ regardless of dimension. At the same time, they show that any good estimator (within an additive gap) for this problem must have a sample complexity that is exponential in d. Their results reveal a significant empirical superiority of the plug-in to state-of-the-art kernel density estimation (KDE) and k-nearest neighbors (kNN) methods. As a motivating utilization of the plug-in approach, they estimate information flows in deep neural networks and discuss Tishby's Information Bottleneck and the compression conjecture, among others.

Information-distilling Quantizers

This paper considers the problem of designing a scalar quantizer for Y to maximize the mutual information between the quantizer's output and X, and develops fundamental properties and bounds for this form of quantization, which is connected to the log-loss distortion criterion.

Information Storage in the Stochastic Ising Model

In this work, Polyanskiy and colleagues initiate the study of information retention in locally interacting systems. One of the main results of this work is an achievability scheme that stores more than bits (in orders of magnitude) for superlinear (in n) times. The analysis of the scheme decomposes the system into $\Omega()$ independent Z-channels whose crossover probability is found via the (recently rigorously established) Lifshitz law of phase boundary movement. Lastly for the zero-temperature case, two order optimal characterizations of $\mathrm{In}(t)$, for all t, are given for the grid dynamics with an external magnetic field and for the dynamics over the honeycomb lattice. In both these setups $\mathrm{In}(t) = \Theta(n)$, for all t, suggesting their superiority over the grid without an external field for storage purposes. They also provide results for the positive but small temperature regime.

Alexander Rakhlin

Alexander Rakhlin continued his work on Contextual Bandits and Reinforcement Learning. Working with D. Foster, D. Simchi-Levi, and Y. Xu, he introduced a family of complexity measures that are both sufficient and necessary for obtaining fast instance-dependent regret bounds, and introduced a new oracle-efficient method that adapts to the high signal-to-noise ratio. On the empirical side, the proposed method for Contextual Bandits outperformed state-of-the-art methods on a large array of datasets. In another line of work, Rakhlin and co-authors studied the problem of continuous control with high-dimensional nonlinear observations, termed RichLQR.

Rakhlin also continued the investigation of the generalization ability of procedures that minimize empirical risk over large classes of functions. Such an investigation is prompted by the surprising performance of overparametrized neural networks. Working with G. Kur proved certain lack of adaptivity of nonparametric regression with fixed design to the simplicity of the model. In contrast, in random design regression, the work uncovered a new parameter that may allow the overfitted solutions to generalize.

The joint work with A. Block and Y. Dagan introduced new techniques for analyzing sequential Rademacher averages, a measure of statistical capacity of a function class that is relevant for online learning. The new techniques parallel the development of Majorizing Measures in the classical theory of Gaussian processes. The work establishes a number of fundamental relationships between sequential fractional covering, sequential scale-sensitive dimensions, and sequential Rademacher averages. The above constitutes the resolution of a number of outstanding open problems in extending the classical theory of empirical processes to the sequential case, and, in turn, establishes sharp results for online learning.

Mardavij Roozbehani

Mardavij Roozbehani led several research efforts on mathematical modeling, optimization, and control for cyber-physical networked systems. The application areas of focus include energy networks, transportation networks, financial networks, and digital or precision farming. The main themes in Roozbehani's research projects are concentrated around models and methodologies for quantifying robustness, efficiency, and risk in energy networks, and understanding the tradeoffs that the system architecture induces between these metrics.

AI and Digital Farming

The long-term goal of this line of research is to empower farmers, particularly in rural Africa and other developing countries, to improve their production through investments in technologies. Traditional investment strategies have the farmers take loans to upgrade their operations by mortgaging their land. As a result, in such settings the investors participate in the profits, but not in the losses that result from external shocks (e.g., adverse weather and pests). This makes the farmers vulnerable to shocks which acts as a deterrent from engaging in these upgrades. The idea is to establish mechanisms to leverage the potential increase (through technology) in productivity and profits to provide an insurance for shocks. The researchers' approach is based on a data sharing platform that incentivizes investors to participate and reward farmers for it. The value of data in this setting is related to the increase in the aggregate welfare pre- and post-adoption of technologies.

In parallel efforts the researchers are exploring application of online learning, in particular reinforcement learning to optimize farming actions such as irrigation and soil fertilization based on the state of soil and crops. The challenge in this line of research is to develop practical and simplified policies that are interpretable and implementable by farmers in rural Africa. Addressing this issue needs deeper understanding of AI algorithms and further advancements in theory and practice.

Devavrat Shah

Devavrat Shah and his research group are currently developing theoretical foundations and algorithmic solutions for questions arising in the context of "social" data processing and decision-making. Social data is the data generated by people through their use of modern, data-generating services such as ecommerce-portals, media, polls, utilities, and more.

Intellectually, this requires developing robust statistical models that capture the universal aspects of social behavior, the ability to do 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 a high-dimensional setting.

Addressing these challenges requires fundamental progress at the interface of statistics, machine learning, computation, and social sciences. Shah's group has been working to address these challenges by making progress on canonical questions in social data processing over the past decade, including learning choice, recommendations, ranking, crowd sourcing, causal inference, and reinforcement learning.

The ongoing research activities in Shah's group involve developing methods for performing causal inference using observational as well as experimental studies. Specifically, they have brought a novel perspective from recent development in Machine Learning to Causal Inference through "Tensor Estimation" to develop such methods. As a consequence, they provide "what if analysis" tools for policy evaluation including the Covid-19 pandemic and personalized medicine.

In addition to developing the methods, Shah's group is developing software systems with extremely easy to use interface to provide broader access. These activities are synergetic to other ongoing activities in terms of data efficient methods for reinforcement learning, time series analysis, and socially responsible Machine Learning.

Shah has also been leading the MicroMasters in Statistics and Data Science to provide access to MIT-level graduate education in the topic more broadly at an extremely affordable tuition offered through edX as part of collaboration of IDSS and Office of Digital Learning.

David Simchi-Levi

David Simchi-Levi, a thought leader in business analytics and supply chain management, is a professor of CEE and IDSS. Simchi-Levi is also editor-in-chief of *Management Science*, one of the two flagship journals of INFORMS, an appointment he has had since 2018.

Simchi-Levi serves as the director of the MIT Data Science Lab where the focus is on the developments of analytic techniques and tools for improving decision making in environments that involve uncertainty and require statistical learning. He achieves this by exploring theoretical foundations of operational problems and applying them in the development of algorithms that integrate machine learning and stochastic or deterministic optimization techniques. The methods developed in the lab have been implemented by a large number of companies across a variety of industries such as airlines, insurance, manufacturing and retail.

Simchi-Levi has developed and taught course 1.275J/IDS.305J Business and Operations Analytics, where students learn about how organizations apply data, machine learning, and optimization to gain insights and make better decisions; 1.266 Supply Chain and Demand Analytics, a course that focuses on effective supply chain and demand analytics for companies that operate globally, with emphasis on how to plan and integrate supply chain components into a coordinated system. Students are exposed to concepts, models and machine learning, and optimization-based algorithms important in supply chain planning, with emphasis on supply chain segmentation, inventory optimization, supply and demand coordination, supply chain resiliency, and flexibility; 1.267 Statistical Learning in Operations, a PhD course that focuses on applications of machine learning methods, combined with operations research techniques, to study a variety of operational problems, from supply chain through revenue management to healthcare management. The class brings together two different disciplines, operations research and computer science to develop both theory and effective techniques for dealing with operational problems.

Suvrit Sra

Suvrit Sra joined EECS as an assistant professor in January 2018, and was promoted to associate professor beginning 2019; he continues as a LIDS PI, which he has been since January 16, 2015. His research interests lie in optimization for machine learning and pure and applied mathematics.

Machine Learning and Optimization

Sra's primary research is in optimization for machine learning. Over the last year, he continued his work on the foundations of geometric optimization as well as on stochastic gradient descent, the workhorse of almost all of modern machine learning. With his student he published work on Riemannian accelerated gradient—which was refined and presented at the COLT 2020 conference virtually. During this year of remote work, his group also discovered, developed, and published a work on shuffling based stochastic gradient methods—the class of methods that are used to train deep neural networks—where tight complexity bounds were shown for the first time. During this period, Sra's research with collaborators broached the topic of the complexity of finding critical points of non-differentiable non-convex functions, a class of functions that is fundamental to machine learning.

During this period Sra also continued to serve as area chair or senior area chair for several leading conferences in machine learning, including Neural Information Processing Systems (NeurIPS), International Conference on Machine Learning (ICML), and others.

John Tsitsiklis

John Tsitsiklis, Clarence J. LeBel Professor of Electrical Engineering, served as LIDS director and IDSS associate director until December 31, 2020. During that period, he was primarily focused on the administrative aspects of LIDS and the transition of LIDS to the Schwarzman College of Computing. This included a thorough review of the lab's DEI aspects.

Since January 2021, he has been on sabbatical leave, and has been exploring the field of reinforcement learning (a subject in which he was engaged 20 years ago), with an eye towards course development as well as new research directions. In addition, he is working on an elementary but rigorous and broad introduction to data science.

On the research side, he is working on finalizing theoretical work on stochastic networks that are operated in the presence of both light and heavy tails. This involves the development of a variant of the powerful fluid-model methodology for the analysis of stochastic networks, a variant that can take into account outlier events caused by heavy tails.

Caroline Uhler

Caroline Uhler, associate professor of EECS, carries out research in the areas of machine learning and statistics with applications to genomics. Her current research is centered around four interconnected pillars: causal inference, generative modeling, gene regulation, and, drug discovery. In recognition of her work in this area, she was invited to serve as the co-director of the newly launched Eric and Wendy Schmidt Center, a $250 million endowed center, at the Broad Institute devoted to understanding the programs of life.

Overparameterized Autoencoders and Drug Repurposing

While deep networks used in practice are often over-parameterized (i.e., large enough to perfectly fit training data,) these networks perform well on test data, which seemingly contradicts the notion of overfitting. Since representation learning is key in many biological applications, the group focuses on neural networks used in generative modeling (autoencoders, GANs, flow-based models) to understand this phenomenon. Uhler's PhD student, Adit Radhakrishnan, showed in recent work that while over-parameterized autoencoders have the capacity to learn the identity map, they are self-regularizing and instead learn functions that are locally contractive at the training examples.

This work appeared in *PNAS* and built the basis for the group's work on drug repurposing, which was developed in light of the Covid-19 pandemic crisis. In particular, they used over-parameterized autoencoders for embedding data from large-scale drug screens and identify drug signatures that are generalizable across different cell types. In this way, they were able to predict the effect of FDA approved drugs on SARS-CoV-2 infected lung epithelial cells and identify drug candidates for the repurposing against Covid-19. The group was excited to see that Sanofi recently started a trial on RIPK1 (the target that we identified) inhibitors for Covid-19. This work appeared in *Nature Communications* and was also highlighted by MIT News.

Autoencoders for Multi-Modal Translation

To overcome the experimental limitations in linking spatial and biochemical dimensions in cells, PhD student Karren Yang developed a methodology for translating between imaging and sequencing modalities by coupling autoencoders in the latent space and validated it experimentally. This work appeared in *Nature Communications*. Building on it, she also developed a framework for molecule-to-image synthesis—to produce the image corresponding to the effect of an unseen molecule on a cell as a promising avenue for virtual drug screening. This work was also presented at the Conference on Computer Vision and Pattern Recognition (CVPR) 2021.

Kalyan Veeramachaneni

Veeramachaneni joined LIDS in 2016 as a principal research scientist where he heads the Data-to-AI Group. His group focuses on building large-scale AI systems that work alongside humans, continuously learning from data, generating predictions and integrating those predictions into human decision-making. The group develops foundational algorithms, abstractions, and systems to enable these three tasks at scale. Algorithms, systems and open-source software developed by the group are deployed for applications in the financial, medical, and education sectors.

Cardea: An Open Source Automated Machine Learning Framework for Electronic Health Records

The past decade has seen the development of a number of data-driven machine learning models meant to tackle problems in healthcare. However, such a high level of expertise is needed to build, customize, and use these models that many remain effectively inaccessible—a situation exacerbated by data gaps and a shortage of machine learning experts.

To bring down this barrier to entry, Veeramachaneni and his team built Cardea—the first ever open-source, end-to-end automated machine learning framework for creating predictive models from electronic healthcare data. In developing Cardea, the team overcame data quality and availability issues that have previously made standardized healthcare data difficult to work with by defining abstractions and intermediate data representations. They also created a complete end-to-end framework, incorporating an adaptive data assembler, an automated feature extractor, and an automated model tuning system.

Cardea enables even users without machine learning experience to build working predictive models and use them to obtain metrics, reports and recommendations. It can adapt to different scenarios across multiple healthcare datasets, and is competitive with human performance across a number of dimensions. Cardea was presented at the IEEE 7th International Conference on Data Science and Advanced Analytics in October 2020.

Using Machine Learning to Assist Experts in Finding Anomalies in Time Series

Recent machine learning-based approaches to time series anomaly detection learn a model that either predicts or reconstructs a time series, compare this with the time series' real values, and use any discrepancies to detect anomalies. Veeramachaneni, Dongyu Liu (postdoctoral researcher), Alexander Geiger (visiting research student), and Sarah Alnegheimish (master's student), in collaboration with Professor Alfredo Cuesta-Infante from the University of Ray Juan Carlos, approached anomaly detection through a particular deep neural network technique called Generative Adversarial Networks (GANs).

Their resulting anomaly detection tool, Time Series Anomaly Detection GAN (TadGAN), outperformed eight other baseline techniques in an extensive experiment using 11 time-series datasets from three reputable entities—NASA, Yahoo, and Numenta—achieving the best performance score in most datasets (six out of 11). TadGAN improved on a more traditional technique, AutoRegressive Integrated Moving Average (ARIMA), by 15.3%—the highest advance. The team presented their work at the annual IEEE International Conference on Big Data in December 2020.

Ashia Wilson

Ashia Wilson, Lister Brothers (Gordon K. '30 and Donald K. '34) Professor and assistant professor, recently joined the EECS faculty in January 2021. Her main research focuses on developing robust and fast algorithms to scale to solve important problems using machine learning. The research draws heavily on advances in dynamical systems, statistics, and optimization theory. Currently, machine learning is used to develop risk-scores which inform decision-making across a variety of sectors. Her more recent research focuses on formalizing the societal impact of risk scoring, particularly within the health sector. To that end, Wilson is currently collaborating with Professor Marzyeh Ghessimi and the Federation of American Science to address health inequity in organ donation, using data from six organ procurement organizations.

Moe Win

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

To advocate outreach and diversity, the group is committed to attracting—and has a strong track record of actively recruiting—graduate and undergraduate students from underrepresented minority (URM) groups and giving them exposure to theoretical and experimental research at all levels.

Current research topics being investigated by Win and his group include network localization and navigation, multi-object tracking, network interference exploitation, intrinsic wireless secrecy, adaptive diversity techniques, ultra-wideband systems, and quantum information science. Accomplishments for a few specific projects are summarized below.

Network Localization and Navigation

The group has made notable contributions in the field of network localization and navigation from multiple aspects. In particular, the group developed network localization and synchronization (NLS), a new paradigm that jointly considers localization and synchronization to achieve performance gains in a completely asynchronous wireless network.

In collaboration with Sanjoy Mitter, the group also developed real-time encoding strategies for distributed filtering problems under communication constraints. In particular, the designed strategy employs channel feedback and enables efficient encoder implementations.

Moreover, it has continued the study of node deployment problems. Node deployment is challenging in practice due to various uncertainties present in the positions of the deployed nodes. The group developed a framework for the design of optimal network geometry under bounded disturbances in the positions of the sensing nodes.

In addition, the group has continued the development of a paradigm for scalable multi object tracking (MOT) and network operation for multi-agent MOT applications. In particular, the group further derived Bayesian inference algorithms for localizing and tracking extended objects in the presence of data association uncertainty.

Quantum Information Science

Entanglement is a unique property in quantum mechanics that serves as a valuable resource for many important quantum operations. In this context, the group has devoted its effort to establishing entangled qubit pairs between agents that are far apart. Moreover, the group has designed remote entanglement distribution (RED) protocols that maximize the entanglement distribution rate. The group has also investigated queuing delay in quantum networks and introduced a tractable model for analyzing the queuing delay of quantum data, referred to as quantum queuing delay. Using this model, the group developed a cognitive-memory-based policy for memory management and showed that this policy can exponentially decrease the average queuing delay with respect to memory size.

The ability to distinguish between two given quantum states, also known as quantum state discrimination (QSD), plays a key role in various applications such as quantum sensing and quantum communication. The group addressed this discrimination issue in the context of a family of quantum states, which go by the name of photon-added coherent states (PACSs). The group showed that the use of PACSs instead of coherent states with the same energy can significantly improve the QSD performance.

Cathy Wu

Cathy Wu started in 2019 as the Gilbert W. Winslow (1937) Career Development Professor and assistant professor of CEE and IDSS, and as a PI in LIDS. Working at the intersection of machine learning and mobility, her group designs algorithms to make sense of and shape future cities. Wu's group has grown to five PhD students. In response to the Covid-19 pandemic, the group quickly restructured around more collaborative projects and virtual co-working activities. Recent research includes:

Flow: A Modular Learning Framework for Mixed Autonomy Traffic

The rapid development of autonomous vehicles (AVs) may transform mobility through improved safety, efficiency, and access. However, the progression of these impacts, as AVs are adopted, is not well understood. Wu studied the suitability of deep reinforcement learning (RL) for overcoming long-standing challenges in analyzing mixed human and AV traffic. A modular learning framework leverages RL to analyze traffic "LEGO" modules that capture common traffic phenomena (stop-and-go traffic, lane changing, intersections). With only 5–10% AVs, learned AV control laws are found to exceed human-only driving performance by at least 40% in system-wide velocity, and they eliminate stop-and-go traffic. This first-author paper appeared in the IEEE Transactions on Robotics.

Learning to Delegate for Large-scale Vehicle Routing

Mobility is riddled with large-scale combinatorial problems, such as vehicle routing problems (VRPs), and the problems change as the mobility system evolves. Machine learning methods have the potential to adapt to new combinatorial problems; however, at present, such methods are seldom competitive with classical heuristics. Focusing on VRPs, a learning-augmented algorithm was designed, which learns to delegate appropriate subproblems to a black box subsolver. The method achieves state-of-the-art performance, with up to a 15 times speed-up, on large VRPs. A pre-print is available of this joint work with students Sirui Li and Zhongxia Yan.

Events and Communications

LIDS continues to organize its signature events, which were all held virtually this year: the broadly attended LIDS Seminar Series, and the LIDS Student Conference, a student-run conference that celebrated its 26th year in spring 2021, which provides an interactive forum for students to discuss their research, and features several distinguished plenary speakers each year.

LIDS faculty also remain involved in the organization of major workshops and conferences, such as this year's Learning for Dynamics and Control (L4DC) workshop, now in its third year and co-organized by Professors Ali Jadbabaie and Pablo Parrilo, which brought together experts in machine learning and AI together with researchers in control theory and robotics. Also held virtually, the event was attended by more than 6,300 people worldwide.

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 include the annual Women in Data Science Conference, Cambridge—jointly presented by Harvard University and MIT, and co-organized by Caroline Uhler; held virtually this year—and the weekly LIDS and Stats Teas, which provide students and postdoctoral researchers an opportunity to give brief research presentations to the community in an informal setting, also held virtually this year.

The lab also continued to produce content for its annual community-oriented magazine, LIDS|ALL, which consistently receives great praise. LIDS|ALL features articles on important events related to LIDS as well as profiles of LIDS community members including students, faculty, alumni, and staff.

Awards

Dimitri Bertsekas received the 2022 IEEE Control Systems Award.

Matthew Brennan (supervised by Guy Bresler) won the Best Student Paper Award at COLT2020. Notably, he also received this award at COLT2018, for related work, with Professor Bresler and collaborator.

Professor Luca Carlone was a Best Conference Paper Finalist at the International Conference "Robotics: Science and Systems"" (RSS 2021). He also received the Outstanding Associate Editor Award at International Conference on Robotics Automation 2021 and the distinction of Outstanding Reviewer at Computer Vision Pattern Recognition 2021. Further honors include an NSF CAREER Award, 2020 Best Paper Award Honorable Mention from the IEEE Robotics and Automation Letters, and Track Best Paper Award at the 2021 IEEE Aerospace Conference.

Professor Jonathan How received a 2020 Best Paper Award Honorable Mention from the IEEE Robotics and Automation Letters. Professor How also received a 2020 Amazon ML Research Award as well as a 2020 IEEE CSS Distinguished Member Award.

Staff member Francisco Jaimes received the Schwarzman College of Computing Infinite Mile Award for Diversity and Community.

Student Igor Kadota received the MIT School of Engineering Graduate Student Extraordinary Teaching and Mentoring Award.

Student Dennis Shen, supervised by Professor Devavrat Shah, won the George M. Sprowls PhD Thesis Award in Artificial Intelligence and Decision Making.

Professor David Simchi-Levi was awarded the INFORMS Impact Prize. Professor Simchi-Levi also won the 2020 Koopman Award, and the 2020 Best Paper (theoretical track) in the Workshop on Data Mining and Decision Analysis.

Other Honors

Professor Luca Carlone was promoted to associate professor without tenure by the Department of Aeronautics and Astronautics, effective July 1, 2021.

Professor Jonathan How was elected to the National Academy of Engineering in 2021.

Senior Research Scientist Marija Ilic was elected to National Academy of Engineering in 2021.

Professor Asu Ozdaglar was named a 2021 IEEE Fellow.

Professor Alexander Rakhlin was promoted to full professor by BCS, effective July 1, 2021.

Professor Devavrat Shah was named Andrew (1956) and Erna Viterbi Professor of Electrical Engineering and Computer Science by EECS, effective July 1, 2021.

Professor Caroline Uhler was invited to serve as the co-director of the newly launched Eric and Wendy Schmidt Center at the Broad Institute devoted to understanding the programs of life. Professor Uhler was also elected a council member of the International Statistical Institute.

Organizational Aspects

Professor Sertac Karaman started his role as the director of LIDS on July 1, 2021. Prior to his appointment, Professor Eytan Modiano, who was the associate director of the lab from 2018–2020, served as the interim director from January 1, 2021 to June 31, 2021. Prior to this, Professor John Tsitsiklis served as the director of LIDS from April 1, 2017 to December 31, 2020.

Key Statistics for AY2021

- Faculty PIs: 29
- Research staff PIs: 4
- Affiliate members: 9
- Administration, technical, and support staff: 11
- Postdocs and other research staff (non-PI): 38
- Visitors and other affiliates: 38
- Graduate students: 145
- Visiting students: 2

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 provides a central component underlying many of the 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.

Besides fundamental research, LIDS is engaged in furthering collaborative efforts that balance theory and practice, for maximal impact. The umbrella provided by the Schwarzman College of Computing and the resulting opportunities for cross-cutting collaborations are very helpful in this respect.

Finally, while LIDS is a research-oriented entity, LIDS 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.

Sertac Karaman
Director
Associate Professor of Aeronautics and Astronautics