Laboratory for Information and Decision Systems

The Laboratory for Information and Decision Systems (LIDS) is an interdepartmental laboratory for research and education in systems, control, optimization, communication, networks, and statistical inference. These disciplines, which span the domain of the analytical information and decision sciences, play a critical and pervasive role in science, engineering, and society more broadly. LIDS continues to be at the forefront of research in traditional core disciplines in this area. Over the past few years, the scope of LIDS research has broadened to include new emerging areas at the intersection of several fields including game theory, social and economic networks, efficient large-scale inference (using optimization, statistics, and algorithms), and autonomous systems. LIDS provides an intellectually cohesive and interactive environment that fosters the research needed for the future and instills in our students the disciplinary depth and interdisciplinary understanding required of research and engineering leaders of today and tomorrow.

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. As a result of the interdisciplinary nature of recent focal work and the pervasiveness of the analytical methodology utilized by LIDS researchers, the laboratory has also built strong collaborations and interactions with many other areas at MIT, including the Computer Science and Artificial Intelligence Laboratory, the Research Laboratory of Electronics, the Operations Research Center (ORC), the Media Laboratory, the Harvard-MIT Division of Health Sciences and Technology, the Department of Civil and Environmental Engineering, the Department of Mechanical Engineering, the Department of Economics, and the Sloan School of Management. LIDS faculty members play leadership roles in major new initiatives involving applications of critical importance to society. These initiatives include projects focusing 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), and social, economic, and financial networks in close collaboration with Economics and Sloan.

An important development this year is that LIDS has joined a new entity, the Institute for Data, Systems, and Society (IDSS), that brings in statistics, social science, and application domain expertise. IDSS will build on the tradition of cutting-edge research in information and decision sciences spearheaded within MIT by LIDS. Our lab's vision and members have played a crucial role in forging IDSS's intellectual agenda and will continue to do so under the leadership of professor Munther Dahleh, the inaugural IDSS director and previously LIDS's interim director.

This year, LIDS is also excited to welcome new members to our community. Suvrit Sra joined LIDS as a principal research scientist in January 2015. Sra's expertise includes large-scale machine learning, optimization, and matrix analysis, and he brings a computational/optimization perspective on machine learning problems. We are also delighted to welcome Guy Bresler and Caroline Uhler, both from the Department of Electrical Engineering and Computer Science. Bresler, whose expertise includes high-dimensional inference in the context of graphical models, information theory, and biology, will be joining the LIDS faculty in September 2015. Uhler will be joining in October 2015 and brings in expertise in algebraic statistics, combining algebraic geometry and convex optimization to develop new paradigms and algorithms for data analysis. Together with our current faculty members in these areas, these excellent additions enable us to form a critical mass of researchers in statistics, optimization, and machine learning.

LIDS researchers continue to have great success in obtaining funding for our broad and deep research agenda, and we continue to develop our relationships with industrial organizations and national laboratories including Draper Laboratory, Lincoln Laboratory, the Los Alamos National Laboratory, the Argonne National Laboratory, Siemens, Honeywell, the Ford Motor Company, Aurora Flight Sciences, and Microsoft Research. 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 continual stream of world-leading researchers as visitors and collaborators.

LIDS Intellectual Vision and Research Areas

The domain of research in LIDS can be described along several different dimensions:

- A set of core analytical disciplines, including probability and statistics, dynamical systems, and optimization and decision theory
- A set of core engineering disciplines, including inference and statistical data processing, transmission of information, networks, and systems and control
- A set of broad challenges in traditional and emerging applications of critical importance to society

Research at LIDS involves activities within and across all of these dimensions: advancing the state of the art in analytical and engineering disciplines within information and decision sciences and addressing fundamental challenges that emerge in applications and problems of relevance to societal needs. The simultaneous existence of these different efforts within the same lab leads to strong synergies among them: work in each of the mathematical disciplines leads to new methodologies that enable advances in core disciplines and in interdisciplinary investigations, and work in attacking those emerging interdisciplinary challenges provides direction and drivers for fundamental disciplinary activities and has led to the charting out of emerging new disciplines.

The availability of increasingly capable sensing, communication, and computation systems enables the collection and transfer of large amounts of data pertaining to complex and heterogeneous interconnected systems. The need for an intellectual platform to simultaneously address questions of data fusion, distributed learning, information transfer, and distributed decision making is stronger than ever, as existing techniques fall short in addressing issues of scalability, robustness, and performance limits. Examples of areas in which LIDS research has and will continue to contribute include the following:

- Coordination of unmanned autonomous systems
- Energy services and information systems
- Large-scale data assimilation for the geosciences
- Network scheduling and routing
- Transportation network analysis, control, and design
- Machine learning for recommendation systems and social media
- Social network analysis and characterization
- Ultra-wideband and other emerging communications technologies
- Intelligence, surveillance, and reconnaissance systems
- Biological systems and biomedical data analysis

Furthermore, the recognition that research within traditional boundaries in information and decision sciences is not adequate to address many of the emerging societal challenges that are ahead of us has motivated LIDS researchers to branch out to areas at the intersection of several disciplines. As a result, we have initiated a set of fundamental research themes that cut across disciplinary boundaries and involve considerable interaction and collaboration with colleagues in other units at MIT 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 design of incentives for large-scale networked, dynamic environments that admit efficient computation
- A unifying foundational framework for modeling and understanding systemic risk
- Foundations of cyber-physical systems (CPSs), including architectural design, security and privacy, cross-layer algorithms, and tools for analysis, verification, and performance guarantees
- Foundational theory for multiscale/multigranularity modeling, including methods for describing complex phenomena at multiple granularities, learning of such models from complex and heterogeneous data, and reduction/simplification of models to levels appropriate for particular questions of analysis or design
- Development of scalable and efficient inference algorithms for problems involving “big data,” in which the boundaries between inference, learning, data representation and access, and massively parallel algorithms are essentially nonexistent

Faculty Activities

Much of the major research activity of LIDS faculty not only cuts across the disciplines, applications, and emerging areas mentioned above but also is collaborative with others within LIDS and elsewhere at MIT.

Dimitri Bertsekas

Professor Bertsekas (McAfee professor of electrical engineering) is interested in deterministic optimization problems and the role of convexity in solving them, possibly through the use of duality. In 2015, he completed a major textbook on convex optimization algorithms that includes some of his recent research on problems whose cost function involves a sum of a large number of component functions. He also completed research on aggregated versions of incremental proximal methods and developed their augmented Lagrangian analogs.

Professor Bertsekas also 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 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.

Robert C. Berwick

Professor Berwick's research during the past year made new advances regarding the biological and computational origins of human language and cognition. It demonstrated that human language evolved separately in two distinctive steps also mirrored in children's language development: (1) vocal learning and production and (2) the ability to combine separate words into phrases. With respect to vocal learning, it was established that the same genomic system, consisting of about 50 genes, assembles roughly the same neural circuits. In children, this system operates from birth to age 1, when children learn the sound system of their language. Professor Berwick's research established that the neural circuits for assembling words into phrases are not fully "wired" at birth but take until about the age of 1½–2 years to develop. This is the point at which children begin to speak, a system that we now know involves a single rule of combination. To understand that system at both the computational and neural levels, Professor Berwick has implemented a parser that also uses just a single rule, following contemporary "minimalist" linguistic theory. He has implemented this parser for English, Japanese, and Arabic, with changes required only in the dictionary that is used. He also constructed several neural circuit models that will serve as a way to test how this parsing model might actually be implemented in the brain.

Summarizing the past several years of efforts in this area, Professor Berwick completed a book with Professor Noam Chomsky, *Language and Evolution*, published by MIT Press.

In addition, Professor Berwick completed the construction of a new public resource database for child language acquisition researchers that, for the first time, permits complex searches and statistical analyses of both text and video-text transcripts of mother-child interactions.

Munther Dahleh

Systemic Risk in Finance

Professor Dahleh (director of IDSS, acting director of the Engineering Systems Division, and acting director of LIDS through September 2015) is studying fire sales and their negative systemic spillovers, which are the main theoretical rationale to prevent the excessive accumulation of short-term funding. Distressed sales by financial intermediaries to meet immediate liquidity demands often cause deep price dislocations transmitted to other market participants through common exposures of their balance sheets, forcing them to also liquidate assets. The result is a self-reinforcing downward spiral in asset prices that impinges on the entire financial system.

In this work, we develop a general equilibrium model of investment with financial frictions that links the severity of fires sales with the likelihood of banking runs, identifying a channel that connects measures of systemic risk with macroprudential regulatory policies. This connection is based on a different kind of fire sale externality that we label credit risk externality. This externality operates through endogenous credit risk constraints and captures how runs on individual financial institutions can disrupt overall financial stability. It arises because banks do not internalize that, by increasing interest rates, an additional unit of fire-sold assets worsens the terms at which others can raise funding and thus increases their probability of default.

The main normative implication is that constrained efficiency can be restored with a Pigouvian (corrective) tax levied on each unit of short-term debt raised by banks. The optimal tax is decomposed in two terms: one that is proportional to the social shadow value of borrowing short term against collateral and another that corresponds to the marginal credit risk externality at the social planner's solution. The marginal credit risk externality captures private agents' overvaluation of short-term debt and is equal to the difference between the marginal change in the probability of a crisis weighted by the real economic costs of such an event and the marginal change in the credit risk of a representative bank weighted by the cost of a run on its short-term liabilities. In this respect, the model illustrates how measures of aggregate systemic risk should discount individual contributions to set the tax at the appropriate level.

Finally, this work offers a distinctive account of how better economic times may lead to higher inefficiencies, thus calling for tighter macroprudential regulation. As investment prospects improve in a second-order stochastic dominance sense, the probability of financial crises decreases. However, because the distribution of returns becomes more "concentrated" around its mean, banks grow less concerned about tail risks and the possibility of damaging runs, and hence they increase their reliance on short-term funding. Interestingly, then, even though the incidence of runs is lower, their severity can actually be greater because of more significant market-wide liquidations.

Robust Network Routing under Cascading Failures

Professor Dahleh continues to study resilience of networks with his collaborators Giacomo Como and Ketan Savla (past postdoctoral fellows). We propose a dynamical model for cascading failures in single-commodity network flows. In the proposed model, the network state consists of flows and activation status of the links. Network dynamics are determined by a (possibly state-dependent and adversarial) disturbance process that reduces flow capacity on the links and routing policies at the nodes that have access to the network state but are oblivious to the presence of disturbance. Under the proposed dynamics, a link becomes irreversibly inactive as a result of overload conditions. The coupling between link activation and flow dynamics implies that links that become inactive successively are not necessarily adjacent to each other, and hence the pattern of cascading failure under our model is qualitatively different than standard cascade models. The magnitude of a disturbance process is defined as the sum of cumulative capacity reductions across time and links of the network, and the margin of resilience of the network is defined as the infimum over the magnitude of all disturbance processes under which the links at the origin node become inactive. We propose an algorithm to compute an upper bound on the margin of resilience for the setting where the routing policy has access only to information about the local state of the network. For the limiting case in which the routing policies update their action as fast as network dynamics, we identify sufficient conditions on network parameters under which the upper bound is tight under an appropriate routing policy. Our analysis relies on making connections between network parameters and monotonicity in network state evolution under the proposed dynamics.

How Networked Agents Make Decisions: Coordination with Local Information

Professor Dahleh, along with his student Spyros Zoumpoulis and Professor John Tsitsiklis, studies decision making by networked entities by examining coordination among strategic agents that share local information—in particular, the role of local information channels in enabling coordination among strategic agents. Building on the standard nite-player global games framework, we show that the set of equilibria of a coordination game is highly sensitive to how information is locally shared among agents. Specifically, we show that the coordination game has multiple equilibria if there exists a collection of agents (1) that do not share a common signal with any agent outside of that collection and (2) whose information sets form an increasing sequence of nested sets. Our characterization thus extends the results on the uniqueness and multiplicity of equilibria in global games beyond the well-known case in which agents have access to purely private or public signals. We also provide a characterization of how the extent of equilibrium multiplicity is determined by the extent to which subsets of agents have access to common information: we show that the size of the set of equilibrium strategies increases with the extent of variability in the size of the subsets of agents observing the same signal. We study the set of equilibria in large coordination games, showing that as the number of agents grows, the game exhibits multiple equilibria if and only if a non-vanishing fraction of the agents have access to the same signal.

Emilio Frazzoli

Professor Frazzoli and his research group pursued research in control theory, algorithmic robotics, and applications to autonomous vehicles, robotic networks, and transportation systems.

Sampling-Based Algorithms for Anytime Control and Estimation

Building on recent breakthroughs, primarily work on asymptotically optimal sampling-based algorithms such as RRT*, Frazzoli and his group continued developing the theory of sampling-based algorithms and their application in planning, control, and estimation problems.

A recent advance is the first asymptotically optimal feedback planning algorithm for nonholonomic systems and additive cost functionals. Our algorithm is based on three well-established numerical practices: (1) positive coefficient numerical approximations of Hamilton-Jacobi-Bellman (HJB) equations; (2) the fast marching method, which is a fast nonlinear solver that utilizes Bellman's dynamic programming principle for efficient computations; and (3) an adaptive mesh-refinement algorithm designed to improve the resolution of an initial simplicial mesh and reduce the solution numerical error. By refining the discretization mesh globally, we compute a sequence of numerical solutions that converges to the true viscosity solution of the HJB. In order to reduce the total computational cost of the proposed planning algorithm, we found that it is sufficient to refine the discretization within a small region in the vicinity of the optimal trajectory. Numerical experiments confirm our theoretical findings and establish that our algorithm outperforms previous asymptotically optimal planning algorithms, such as PRM* and RRT*, in both the number of discretization points and the algorithm running time required to achieve approximately optimal paths of similar quality.

Autonomous Vehicle Development

Self-driving cars are no longer restricted to science fiction but are becoming a reality. In fact, several companies and universities have demonstrated vehicles that can drive autonomously in traffic, in the process building social awareness and pushing the boundaries of current regulations and risk management practices. Professor Frazzoli, primarily through his involvement in SMART and in collaboration with Professor Daniela Rus, led the development of novel, low-cost experimental test beds for autonomous (self-driving) car technologies. The current fleet of autonomous vehicles includes several golf carts and a Mitsubishi iMiEV electric car, called Shared Computer-Operated Transport (SCOT).

A major accomplishment for our group was this year's public trial of an autonomous mobility-on-demand (MOD) service in a public space, the first of its kind to our knowledge. The trial was held at Singapore's Chinese and Japanese Gardens, public-accessible parks located in the western part of Singapore. The mobility-on-demand service operated from 8 am to 2 pm for six days in October and November 2014 and was open to the general public. Throughout the trial, the temperature was in the range of 30.4 to 32.7 degrees Celsius, with humidity ranging from 90% in the morning to 48% in the afternoon. Light rain was encountered during operation on the final day of the trial.

Service was halted only briefly during one period of heavy rain for the comfort of the passengers (the seating area is not completely enclosed).

Over the duration of the trial, the golf cars navigated reliably through all parts of the gardens. The total combined distance traveled by the two golf cars was 351.6 km, as recorded by their odometry systems. The total number of trips was 220. A survey was conducted to obtain user feedback on the trial, and 223 survey forms were received. For most visitors, this public trial was the first time they had used an autonomous vehicle. The trial affirmed our work and was very successful in raising public awareness about autonomous vehicle technology. Users gave an average rating of 4.4 (5 being the best) for their experience with regard to safety and comfort, higher than their perceived safety rating of autonomous vehicles (3.7 out of 5). Users' first-hand experience was critical in gaining their acceptance, as seen from their level of experienced safety and comfort. A video about the pilot with user feedback is available on YouTube.

This successful public trial reinforces our belief that current obstacles to autonomous vehicles are no longer primarily technological but regulatory in nature. Professor Frazzoli is now a member of the Committee for Autonomous Road Transport in Singapore, advising the Ministry of Transport and the Land Transport Authority regarding their efforts to develop regulations supporting the broad adoption of autonomous vehicles in Singapore.

Mobility-on-Demand Systems

A natural question to ask when working on self-driving car technology is the following: what is the point of autonomous cars? Some of the often-cited benefits include increased safety, decreased congestion, and reduced environmental impact. While these are undeniable and desirable benefits, we believe that the main benefit of autonomous vehicles is the enabling of widespread car sharing. Car-sharing services are growing worldwide but typically do not offer one-way, door-to-door rental options. If they do, they often suffer from limited car availability. If shared cars could drive to a customer's pickup location and return to a parking station by themselves upon drop-off, they could offer an unprecedented level of convenience. Financially, car sharing distributes the cost (in terms of dollars and time) of purchasing, maintaining, and insuring autonomous vehicles across a large user base. In addition, autonomous shared cars will eliminate the need to look and pay for a parking spot and will reduce the time needed to walk to and from the parked vehicle.

In recent work, we analyzed performance limitations of mobility-on-demand systems whereby users travel among stations in a network by sharing access to a fleet of either self-driving vehicles or human-driven taxis. Where existing work has focused largely on rebalancing policies to route empty vehicles in systems with stationary demand, we considered the case in which demand for transportation varies with time. We also addressed fundamental tradeoffs among fleet size, rebalancing efforts, and the average queue size of a MOD system. We provide a periodic, time-varying model of these systems; consider reductions in the stationary demand case; and provide a detailed study of a two-station network with time-varying demand. Extensions of these results to more general networks and travel demand profiles are in progress, including ride sharing and data-driven analysis.

Stability and Control of Transportation Networks

Professor Frazzoli and his group also explore modern technologies for analyzing, in real time, massive amounts of traffic data as well as drivers' behavior (e.g., through traditional means such as traffic lights or more innovative concepts such as congestion charging and dynamic pricing). In particular, they have developed a novel distributed algorithm for traffic light control based on the well-known backpressure (or differential backlog) routing algorithm, which ensures maximal throughput for a signalized transportation network. The algorithm is currently at the basis of an agreement with Singapore's ST Electronics and Land Transport Authority for a possible field trial. A simulation-based study has been funded by Singapore's Information Development Authority and Land Transport Authority in preparation for the trial.

Motivated by the observation that traffic flows in urban networks may vary significantly both temporally and spatially, we recently developed a new version of an extended back-pressure (EBP) traffic signal control algorithm. This algorithm can be responsive to different traffic flows by tuning control parameters over both time and location, and it tends to minimize delay at low traffic flows by using a set of so-called green time weights. We show that, under mild conditions, the EBP algorithm with time-varying control parameters can achieve maximum throughput; that is, when the EBP algorithm is adopted, the expected long-term average of total queues is bounded from above for the largest possible set of arrival vectors. A simulation based on real traffic data from Singapore demonstrates the validity of the proposed algorithm.

Neuromorphic Control

Recently developed neuromorphic vision sensors present a high-speed, event-based alternative to conventional vision in robotic systems. We developed a method for the design of event-based controllers that take advantage of the remarkable properties of these sensors to provide low-latency, high-bandwidth feedback control for a large class of dynamical systems. We showed that, under certain circumstances, a simple transformation of the event stream from such a sensor can allow it to be treated as an asynchronous configuration sensor, with minimal computation required to achieve high-speed-output feedback control. These results are applicable to any robotic control problems requiring high-performance visual feedback control with low computation.

Control Theory and Applications

Other research done in the past year encompasses several topics in the general areas of control theory and applications. Example include automated simultaneous state and input estimation, hidden mode tracking for partially observable hybrid systems, and resilient state estimation against switching attacks on stochastic cyber-physical systems.

Jonathan How

Professor 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; sensor network design; and robust, adaptive, and nonlinear control. Professor How is also the principal investigator for the Aerospace Controls Laboratory. Recent research includes the following.

Real-Time Multiagent Decision Making

This area of research addresses the problem of multiagent task allocation in communication-contested environments. The general multiagent task allocation problem is a well-studied topic. However, the majority of research has focused on environments that involve fairly rigid communication and information state assumptions. This work merges three major planning paradigms (offline planners, implicit coordination planners, and plan consensus planners) into a single algorithm, the Hybrid Information and Plan Consensus (HIPC) algorithm, capable of performing in environments that do not fit into the rigid requirements of this set of paradigms. In practice, attempting to merge the behavior of these three paradigms changes the planning problem in a major way. The insight of Professor How's work is that these methods can have complementary advantages if care is taken to properly stitch them together. Offline solutions can provide powerful insights into the aspects that can be modeled and can determine how these modeled effects will shape the overall solution. Even if all of the required planning information is not available a priori, offline methods can reduce the size of the search space that online methods must cover. This can involve everything from scheduling actions such as refueling ahead of time to completely shaping objective functions and completely changing the outcomes of the algorithm at run time. Implicit coordination provides a powerful tool for online coordination. Agents can plan in what are effectively locally centralized teams to provide highly coupled allocations. Finally, plan consensus can be used to enforce assignment constraints that may have been violated due to mismatches in situational awareness across the fleet. Combining these algorithms is a nontrivial endeavor because the stitching together requires that each paradigm know exactly what the others provide and what assumptions they are built on. A naïve combination of these paradigms may lead to inefficient use of computation and communication resources in the best case and full planner failure in the worst case. This work addresses these issues and produces an algorithmic solution that solves the task allocation problem in dynamic and communication-contested environments.

Mission-Focused Information Gathering

Sensor breakthroughs in the past decade have greatly improved the capability of robots to sense complicated, partially known environments. These technologies enable many new capabilities for mobile robots, but they also introduce new algorithmic challenges to process them. This work studies how to extract useful information from large amounts of data using limited resources (computation, communication, and memory) and how to build compact models of the environment from only important information. In the robot navigation application, the robot's mission is to navigate from one point to another without collision. New algorithms are developed to select important features at narrow passages and select measurements to maximize information gain on these features. Both simulation and hardware experiments show that the select features and measurements significantly reduced the data size but still maintained important information to enable collision-free navigation.

Measurable Augmented Reality for Prototyping Cyber-Physical Systems

Cyber-physical systems (CPSs) refer to engineering platforms that rely on the integration of physical systems with control, computation, and communication technologies.

Autonomous vehicles are instances of CPSs that are rapidly growing with applications in many domains. Due to the integration of physical systems with computational sensing, planning, and learning in CPSs, hardware-in-the-loop experiments are an essential step for transitioning from simulations to real-world experiments. We have proposed an architecture for rapid prototyping of CPSs that has been developed in the Aerospace Controls Laboratory. This system, referred to as MAR-CPS (Measurable Augmented Reality for Prototyping Cyber-Physical Systems), includes physical vehicles and sensors, motion capture technology, a projection system, and a communication network. The role of the projection system is to augment a physical laboratory space with autonomous vehicles' beliefs and a simulated mission environment, which in turn will be measured by physical sensors on the vehicles. The main focus of this method is on rapid design of planning, perception, and learning algorithms for autonomous single-agent or multiagent systems. Moreover, the proposed architecture allows researchers to project a simulated counterpart of outdoor environments in a controlled indoor space, which can be crucial when testing in outdoor environments is disfavored due to safety, regulatory, or monetary concerns. We have demonstrated the real-time capabilities of MAR-CPS in a variety of problems in autonomy, such as motion planning, multirobot coordination, closed-loop vision-based perception and planning, and learning of spatiotemporal fields.

Decentralized Partially Observable Semi-Markov Decision Processes

Shayegan Omidshafiei, Ali-akbar Agha-mohammadi, Christopher Amato, and Professor How have developed a sequential decision-making algorithm for multiagent teams. In multiagent decision making under uncertainty, at every time step, each vehicle takes an action and receives noisy and/or partial observations of the environment as well as a joint reward for the team. The most general way to represent this problem is as a decentralized partially observable Markov decision process (Dec-POMDP). Dec-POMDPs have seen a wide range of applications, including multirobot exploration and surveillance. However, they involve worst-case doubly exponential time complexity and are therefore computationally infeasible to solve for large-scale problems. We have developed an abstractification of Dec-POMDPs called the decentralized partially observable semi-Markov decision process (Dec-POSMDP). Dec-POSMDPs are a generalized version of a Dec-POMDP utilizing temporally extended actions (also known as macro-actions). Unlike the primitive or low-level actions used in Dec-POMDPs, macro-actions allow high-level representation of task allocation problems, increasing scalability to large discrete or continuous domains. Although macro-actions have been successfully implemented in single-robot settings, extensions to multirobot settings are nontrivial because of the need for quantifiable certainty in execution time and success probability, and thus these extensions have seen limited implementation.

We have also demonstrated the performance of the Dec-POSMDP in a constrained, health-aware version of the multi-UAV package delivery problem under uncertainty. In addition, we have demonstrated hardware results with four quadcopters showing that the Dec-POSMDP can represent multirobot problems and provide quality solutions for large-scale task allocation domains.

Decoupled Multiagent Path Planning in Nonconvex Domains

Together with students Steven Chen and Mark Cutler, Professor How has developed a multiagent path planning algorithm based on sequential convex programming (SCP) that finds locally optimal trajectories. Previous work using SCP has efficiently computed motion plans in convex spaces with no static obstacles. In many scenarios where the spaces are nonconvex, previous SCP-based algorithms failed to find feasible solutions because the convex approximation of collision constraints leads to the formation of a sequence of infeasible optimization problems. The new work of Professor How and his group addresses this problem by tightening collision constraints incrementally, thus forming a sequence of more relaxed, feasible intermediate optimization problems. They have shown that the proposed algorithm increases the probability of finding feasible trajectories by 33% for teams of more than three vehicles in nonconvex environments. Furthermore, they have shown that decoupling the multiagent optimization problem to a number of single-agent optimization problems leads to significant improvement in computational tractability. They developed a decoupled implementation of the proposed algorithm (dec-iSCP) and showed that it runs 14% faster and finds feasible trajectories with higher probability than a decoupled implementation of previous SCP-based algorithms. The algorithm is implementable in real time and has been validated through hardware experiments on a team of quadrotors.

Smart Shuttles for On-Campus Mobility-on-Demand Systems

Self-driving vehicles have the potential to revolutionize future transportation systems, with mobility-on-demand systems playing an important role. The key to a successful MOD system is the ability to properly model the demand for rides, thereby reducing pickup and transit latencies and improving the customer experience. Autonomous vehicles offer additional sensors that can be used to improve demand modeling for MOD systems.

This project aims to build a MOD shuttle research framework on the MIT campus utilizing vehicles equipped with the same sensors found on self-driving vehicles. The first phase of the work will consist of deploying a set of three human-driven electric golf carts that will transport passengers around the east side of the campus. These vehicles will be equipped with a suite of sensors enabling them to determine their own locations as well the locations of both static and dynamic environmental obstacles. Data collected from the sensors will be used to explore research objectives in the fields of pedestrian prediction, path planning, and MOD queuing theory. Future phases of the work will include the option for these vehicles to perform portions of passenger transportation tasks autonomously.

Predictive Modeling of Pedestrian Motion Patterns with Bayesian Nonparametrics

This project aims to improve the safety of autonomous vehicles by developing a predictive modeling framework for anticipating the future behavior patterns of other mobile agents (e.g., cyclists and pedestrians). This model would allow an autonomous vehicle to account for the uncertainty in other agents' future behavior (e.g., making possible turns) while navigating to its desired location. A promising data-driven approach is to learn motion patterns from previous observations using Gaussian process regression, which are then used for online prediction. Gaussian process mixture models have been subsequently proposed for determining the number of motion patterns. A first phase of the project aims to significantly improve the computational tractability of this model and integrate the model with a risk-aware path planner on board an autonomous vehicle. The project's second phase aims to extract features from the learned models, which in turn would be useful for transfer learning and incorporating the effects of dynamic events (e.g., traffic light patterns). In particular, it would be useful for multiple autonomous vehicles to share and learn from data collected at different locations.

Multiagent Decentralized Control in Partially Observable Stochastic Environments

In decentralized domains with communication limitations, agents cannot share their entire belief states, so execution must proceed based on local information. Decentralized partially observable Markov decision processes provide a general framework for modeling multiagent sequential decision making in the presence of uncertainty. Although Dec-POMDPs are typically intractable to solve for real-world problems, recent research on macro-actions in Dec-POMDPs has significantly increased the size of problems that can be solved. However, existing methods are confined to tree-based policies in finite-horizon problems and assume that the underlying POMDP models are known a priori. To accommodate more realistic scenarios in which the full POMDP model is unavailable and the planning horizon is unbounded, Professor How and postdoc Miao Liu proposed a policy-based reinforcement approach to learning the macro-action policies represented by Mealy machines. Based on trajectories of macro-actions, observations, and rewards generated through interactions with the environment via hand-coded policies (demonstrations) and random exploration, an expectation-maximization (EM) algorithm is proposed to learn decentralized macro-action policies, leading to a new policy learning framework, policy-based EM (POEM), that has convergence guarantee for batch learning. The performance of POEM is demonstrated in two domains, a benchmark navigation-among-movable-obstacles problem and a newly designed large search and rescue problem. Empirical study shows that POEM is a scalable batch learning method that can learn optimal policies and achieve policy improvement over hand-coded (suboptimal) policies for missions in partially observable stochastic environments.

Expectation maximization has recently been shown to be an efficient algorithm for learning finite-state controllers (FSCs) in Dec-POMDPs. However, current methods use fixed-size FSCs and often converge to maxima that are far from optimal. Professor How and Miao Liu considered a variable-size FSC to represent the local policy of each agent. These variable-size FSCs are constructed using a stick-breaking prior, leading to a new framework called decentralized stick-breaking policy representation (Dec-SBPR). This approach learns the controller parameters via a variational Bayesian algorithm without having to assume that the Dec-POMDP model is available. The performance of Dec-SBPR is demonstrated on several benchmark problems, with the results showing that the algorithm scales to large problems while outperforming other state-of-the-art methods.

Dynamic Mission Planning for Human-Robot Teams

Existing approaches to multiagent mission planning do not extend well to scenarios in which people coordinate closely with robotic teammates. By requiring human operator cooperation with autonomous vehicles for the completion of tasks, the challenges of coupled agent constraints and dynamic, stochastic performance are thrust into the planning problem. Reliable prediction of supervisory task execution is difficult, and even reasonable models are subject to time-varying human characteristics (e.g., fatigue and distraction) as well as differences between individuals (e.g., experience and skill). Professor How, along with students Chris Shannon and Luke Johnson, has developed a system that integrates human-in-the-loop performance metrics and constraints into the traditional task allocation and scheduling problem to generate robust schedules for tightly coupled human-robot teams. Additionally, algorithms are utilized within a closed-loop framework for time-extended replanning with highly dynamic agents and environments. The efficacy of the approach has been validated in a variety of coordinated human-robot missions.

Reinforcement Learning via Multifidelity Simulators

Reinforcement learning (RL) can be a tool for designing policies and controllers for robotic systems. However, the cost of real-world samples remains prohibitive, as many RL algorithms require a large number of samples before learning useful policies. Simulators are one way to decrease the number of required real-world samples, but imperfect models make deciding when and how to trust samples from a simulator difficult. Professor How and student Mark Cutler have developed a framework for efficient RL in a scenario where multiple simulators of a target task are available, each with varying levels of fidelity. The framework is designed to limit the number of samples used in each successively higher fidelity/cost simulator by allowing a learning agent to choose to run trajectories at the lowest level simulator that will still provide it with useful information. How and Cutler have derived theoretical proofs of the framework's sample complexity and demonstrated empirical results on a remote-controlled car with multiple simulators. The approach enables RL algorithms to find near-optimal policies in a physical robot domain with fewer expensive real-world samples than previous transfer approaches or learning without simulators.

Hybrid Model Reference Adaptive Control for Unmatched Uncertainties

Adaptive control can be used to achieve desirable levels of performance in systems with uncertain dynamics by combining parameter estimation with control. However, when dealing with underactuated systems, previous work has been limited to a restrictive class of problems wherein uncertainties are directly matched to control inputs (matched uncertainties). Professor How and student Jack Quindlen have extended recent model learning methods to develop a framework that expands adaptation to include uncertainties not directly matched to control inputs (unmatched uncertainties). This framework not only increases the robustness of the adaptive system to unmatched uncertainties but simultaneously improves convergence toward the desired optimal trajectory.

Multiagent Planning and Learning for Disaster Rescue

This project applies the lab's multiagent planning and reinforcement learning approaches to control autonomous aircraft used in tracking and fighting disasters such as forest fires. Decentralized reinforcement learning algorithms decompose the learning problem among agents under communication constraints and improve upon robust multiagent planning procedures. This integrated planning and learning implementation is able to react to contingencies in the dynamic and stochastic forest fire environment while maintaining mission objectives and overall flight safety. Hardware emulations in the MAR-CPS environment have demonstrated successful collaborative aerial firefighting of a partially observable forest fire.

Patrick Jaillet

The research of Professor Jaillet (Dugald C. Jackson Professor and ORC Co-Director) has primarily focused on formulating and analyzing online and dynamic versions of classical optimization problems such as the shortest path problem, the traveling salesman problem, the assignment/matching problem, and the matroid secretary problem, as well as some of 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 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, data communication and sensor networks, and/or autonomous multiagent systems, 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 one postdoc (Le Hoang, EECS/LIDS), 10 graduate students from ORC (Maximilien Burq, Serareh Borjan, Arthur Flajolet, Chong Yang Goh, Virgile Galle, Swati Gupta, Nikita Korolko, Maokai Lin, Sebastien Martin, and Konstantina Mellou), two graduate students from EECS (Dawsen Hwang and Andrew Mastin), and one graduate student from Leaders for Global Operations/EECS (Kfir Yeshayahu). The research group in Singapore included three postdocs from SMART (Sanjay Jena, Jie Chen, and Ali Oran) and several graduate students from the National University of Singapore, Nanyang Technological University, and Singapore Management University.

Current funded research programs originate from the National Science Foundation (NSF) ("Online Optimization for Dynamic Resource Allocation Problems"), the Office of Naval Research (ONR) ("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 nine other MIT principal investigators).

Sertac Karaman

Charles Stark Draper Assistant Professor Karaman 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 data-driven application systems. His current work focuses on joint sensing and control for agile robotic vehicles, high-performance robotic networks, and information-theoretic methods in robot motion.

Control Design for Vehicles Operating in Complex Environments under Complex Constraints

This area of research deals with designing efficient computational methods for vehicles with complex dynamics operating in environments involving obstacles under uncertainty.
An example is a high-performance mobile robotic vehicle (e.g., a rotary-wing aerial vehicle) that is tasked with flying inside a building as fast as possible. This navigation problem requires solving (in real time) a control problem in which the 12-degrees-of-freedom state of the robot must be controlled effectively while the robot is navigating at high speeds in a complex environment. The adverse effect of the robot's nonholonomic differential constraints is amplified at high speeds, limiting the robot's maneuvering capability. The geometric constraints impose hazards that must be reliably avoided.

Unfortunately, computing such control laws is extremely challenging. The problem is NP (nondeterministic polynomial-time) hard, with an increasing number of degrees of freedom. Hence, it is unlikely that there exists an efficient algorithm with running time that scales polynomially with increasing degrees of freedom. This phenomenon is often called the curse of dimensionality.

In our recent work, we propose a novel algorithm that runs in polynomial time for all problem instances that admit a certain 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 toward an optimal one. We rigorously prove that the new compression-based algorithm runs in polynomial time with increasing degrees of freedom. The algorithm also scales polynomially with the "rank" of the value function. Hence, if the value function has a low-rank structure due to, for example, geometry and physics (in other words, if the value function is "compressible"), the new algorithm provides substantial computational savings. Effectively, it breaks the curse of dimensionality for problems that exhibit a low-rank, compressible cost-to-go function. From a technical perspective, the compression is enabled by a certain kind of tensor decomposition known as the tensor-train decomposition algorithm, which is similar to matrix decompositions such as the singular value decomposition.

The resulting algorithm is capable of solving high-dimensional problem instances that lacked full numerical solutions until now. In particular, we have used the algorithm to compute the optimal controller for a glider attempting to perch on a wall. The problem involves a seven-dimensional state space, and the full numerical solution to this algorithm has heretofore never been obtained. Our algorithm computes the solution in approximately 10 minutes. To compare, we estimate that a naïve implementation of the well-known value iteration would require more than 100 years to compute a solution with the same quality using the same computational hardware. The improvement in computation time is already eight orders of magnitude. (Joint work in this area involves graduate student Alex Gorodotsky and MIT Professor Youssef Marzouk.)

Information-Based Planning Algorithms for Mapping and Persistent Monitoring

This area investigates planning algorithms that can govern mobile sensors to collect the most valuable information. In our research, we consider the problem of robotic monitoring of discrete events occurring in a large number of stations, where the precise times of arrivals are not known but their statistics are assumed to be available. Earlier we had reduced the resulting complex inference and control problem to a quasi-convex optimization problem in one variable that can be solved efficiently. Our research in this area has led to a better understanding of some widely studied problems. Our recent work in this direction considers problems involving uncertainty, such as when event arrival rates are unknown a priori. We develop learning algorithms that estimate arrival rates on the fly, and we prove performance guarantees for the resulting algorithms. (Joint work involves Professor Girish Chowdhury of Oklahoma State University.)

Sanjoy Mitter

Professor Mitter's research has focused on the subject of manifold learning from data. Given a fixed but unknown probability distribution in a separable Hilbert space, and given independent and identically distributed data, the problem is to test whether the data reside on or arbitrarily close to a smooth manifold belonging to a particular class of manifolds and, if the answer is positive, to construct a manifold from this class. A solution to this problem is presented in joint work with Charles Fefferman of Princeton and Hari Narayanan of the University of Washington (and a former postdoc at LIDS) that will appear in the prestigious *Journal of the American Mathematical Society*. The solution uses ideas from computer science, giving complexity bounds on the data for a positive answer and differential geometry (theory of fiber bundles). Work is currently in progress on the algorithmic aspects of the problem.

Professor Mitter's research on maximum work extraction and implementation costs for nonequilbrium Maxwell demons, conducted jointly with Henrik Sandberg (KTH Royal Institute of Technology), Jean-Charles Delvenne (Université catholique de Louvain), and Nigel Newton (University of Essex), has been published in *Physical Review*.

Eytan Modiano

Professor Modiano (Associate Department Head of Aeronautics and Astronautics) 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 aerospace networks that are cost effective and scalable and meet emerging needs for high-data-rate and reliable communications. In order to address critical needs in the areas of military communications, space exploration, and Internet access for remote and mobile users, future aerospace networks will depend upon satellite, wireless, and optical components. Satellite networks are essential for providing access to remote locations lacking in communications infrastructure, wireless networks are needed for communication between untethered nodes (such as autonomous air vehicles), and optical networks are critical to the network backbone and in high-performance local area networks. The group is working on a wide range of projects in the area of data communication and networks with application to satellite, wireless, and optical networks.

During the past year, CNRG continued to work on an ONR-funded project on the design of practical network control algorithms; this research is based on theories developed by Professor Modiano and his students over the past decade. The algorithms have been shown to optimize network performance (e.g., throughput and utility) but so far have been largely limited to theoretical frameworks. During the past year, the group developed new optimal routing algorithms that work efficiently with the Transmission Control Protocol, the commonly used Internet transport protocol. This new approach will facilitate adaptation of new optimal routing schemes into networks used in practice.

In a related project, funded by the National Science Foundation, the group is developing fundamental limits on the amount of control information exchange needed to effectively control a communication network. Network algorithms, such as channel access algorithms used to schedule transmissions in a wireless network in order to avoid interference, rely on information exchange between nodes in the network. Such information exchanges amount to control overhead that consumes precious amounts of bandwidth. The goal of this project is to develop fundamental limits on the amount of overhead needed to control a network that will inform the design of new and efficient protocols. This past year, Professor Modiano and his student Matt Johnston studied the amount of protocol information needed for scheduling links in wireless networks. In particular, they characterized the tradeoff between distributed protocols, which require a minimal amount of control information, and centralized protocols, which require complete information exchange. They showed that when taking into account the required information exchange, distributed protocols achieve better throughput performance than centralized protocols in certain settings.

Over the past year, the group began work on a new project addressing the robustness of interdependent networks. Many engineering systems involve interactions between two or more networked systems. Cyber-physical systems, for example, consist of networked computer systems (the cyber portion) that are used to control a physical system such as a power grid, water or gas distribution system, or transportation network. 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, with failures in the cyber network leading to failures in the physical network and vice versa. The group has been studying such interdependence failure cascades, both under abstract models of interdependent networks and in the context of power grids and the communication networks used to control them.

In recent years, Professor Modiano and his group have been pursuing industrial collaborations to increase the impact of their work on practical systems. To that end, during the past year, the group started a new collaboration with Qualcomm on mission-critical communications. The collaboration is supported by a gift from Qualcomm that will help fund the group's activities in this area. The group also continues to collaborate closely with researchers at Lincoln Laboratory on the design of network architectures and protocols for military communications. In particular, Professor Modiano has been collaborating with Dr. Brooke Shrader of Lincoln Laboratory, and together they advise a Lincoln Scholar (Thomas Stahlbuhk) who is pursuing his PhD at LIDS.

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

Asuman Ozdaglar

Professor Ozdaglar's research group focuses on modeling, analysis, and optimization of large-scale, dynamic multiagent networked systems. Their 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 of these systems.

A major current research area in Professor Ozdaglar's group is sociotechnological networks, which include communication, decision, and power networks. The operation and failures of such networks depend not only on their engineering design but also on the human element—the intentions, information, and strategic behavior of the users and participants. Professor Ozdaglar's work has integrated the interplay of the human element and engineering aspects in the context of networks.

One strand of her work focuses on developing models and control mechanisms for dynamic processes (e.g., opinion dynamics and epidemics) over networks. In recent work, conducted jointly with graduate student Yongwhan Lim and postdoctoral associate Alex Teytelboym, she developed a stochastic linear threshold model for diffusion of innovation in networks. Previous efforts focused on deterministic versions of this model in which agent thresholds are fixed, making the analysis intractable. We provide explicit analytical characterizations for expected numbers of adopters when thresholds are random in terms of a novel network centrality measure. These characterizations allow us to study network design questions when the seed set is random or targeted. We also study competition over networks (e.g., two firms spending resources to influence purchase decisions) when adoption dynamics are characterized by the stochastic linear threshold model.

Many contagion processes over large networks can lead to costly cascades unless they are controlled by outside intervention. Examples include epidemics spreading over a population of individuals, viruses attacking a network of connected computers, and financial contagion in a network of banks. In a recent project, conducted jointly with Professor John Tsitsiklis and student Kimon Drakopoulos, we studied how this type of contagion can be prevented or contained by dynamically curing some of the infected nodes under a "budget" constraint on the amount of curing resources that can be deployed at each time. We focused on developing dynamic (closed loop) control policies that use real-time feedback about network states, as opposed to the static policies commonly studied for such situations that do not exploit the inherently dynamic and changing nature of the problem. This work provides an explicit characterization of networks that enables rapid containment of the epidemic and devises efficient control policies whenever it is possible to do so. These efforts are supported by an Army Research Office joint multidisciplinary university research initiative (with the University of Pennsylvania, Stanford, and Cornell) and Draper Laboratory's directed research and development program.

Professor Ozdaglar's recent work focuses on design of incentives in infrastructure networks, such as transportation and power networks, to improve the efficiency of the equilibrium emerging from strategic interactions of users. Road traffic congestion, especially at peak hours, is a serious issue in many big cities in the United States and all around the world. A number of users rely on a variety of GPS-based apps (e.g., Waze) during their commute, which provide real-time traffic information to improve congestion and travel time. In a collaboration with Professor Daron Acemoglu from MIT's Department of Economics, Professor Azarakhsh Malekian from the University of Toronto, and graduate student Ali Makhdoumi, Professor Ozdaglar is investigating the efficiency implications of providing more information (about possible additional routes) to a subset of users. Our approach is based on a generalization of a classic traffic flow model using Wardrop equilibrium. We show the non-intuitive fact that, for some network topologies, providing more information to users may lead to increases in their travel time. We then provide a sharp characterization of information structures and network topologies that lead to improved user utility with more information.

In another series of projects, Professor Ozdaglar is studying market-based mechanisms for efficient allocation of power in decentralized electricity markets. Traditional operation of electricity markets involves the market operator (i.e., the independent system operator) forecasting a demand profile over a time horizon (for example, over 24 hours in the day-ahead market) and choosing the prices such that the supplier (generator) cost is minimized while ensuring that supply is matched to demand at each point in time. The generators participate in this market by bidding their supply curves (price and quantity produced). This operation ignores the heterogeneity of user demand on the consumer side and does not involve consumers actively participating in the market. In a recent paper (with former graduate student Ermin Wei, now an assistant professor at Northwestern University, and Professor Azarakhsh Malekian), Professor Ozdaglar provides a competitive model of a market structure in electricity networks that incorporate user heterogeneity together with adjustment costs due to ramp-up and ramp-down constraints of the generators. In this work, we characterize the competitive equilibrium and provide an optimization framework for its decentralized computation. Also, we use the optimization formulation to introduce a systematic framework with storage for analyzing and controlling price volatility. In another project (with postdoctoral associate Ali Kakhbod), Professor Ozdaglar studies market power of generators in deregulated wholesale markets. This project develops an oligopoly model of competition with conventional and wind energy and investigates the resulting market prices as a function of wind penetration into the market and diversification of portfolios of conventional thermal energy companies. This work is supported by an NSF Cyber-

Physical Systems grant with Berkeley, Michigan, and Vanderbilt and a joint Masdar Institute/MIT project.

Another strand of her work shows how interactions over economic and financial networks can lead to the amplification and propagation of small shocks into systemic cascades. A recent project (with Professor Acemoglu and Professor Alireza Tahbaz-Salehi from Columbia University) investigates the cascade effects that arise in a production economy with an input-output structure whereby shocks to some sectors spread to their downstream sectors and beyond. It provides a general framework for analyzing the relationship between the network structure of an economy and its aggregate volatility. In another joint paper, she focuses on interlinkages created by financial transactions (counterparty relations). This paper shows that contagion in financial networks exhibits a form of phase transition as interbank connections increase. In particular, as long as the magnitude and the number of negative shocks affecting financial institutions are sufficiently small, more “complete” interbank claims enhance the stability of the system. However, beyond a certain point, such interconnections start to serve as a mechanism for propagation of shocks and thus lead to a more fragile financial system.

Professor Ozdaglar also investigates mechanism and market design, focusing on provision of incentives to selfish agents to align their performance with a system-wide objective. A recent project (with Professor Pablo Parrilo and Professor Ozan Candogan from Duke University) addresses efficient (i.e., social welfare maximizing) iterative auctions for selling multiple items. Iterative multi-item auctions are employed widely in practice in a number of applications, including spectrum and procurement auctions. Despite their ubiquity, however, the auctions used in practice usually lack optimality guarantees. This paper focuses on valuation functions that admit a compact graphical representation (a natural assumption that holds in practical settings) and provides efficient iterative auctions with simple pricing structures. In another project (with Professor Acemoglu and Professor Mohamed Mostagir from the University of Michigan), she studies crowdsourcing, where the goal is to organize a crowd of individuals for achieving tasks that a single human being and computer cannot perform alone. This work provides a mathematical framework to analyze the problem of assigning and pricing innovation tasks in a crowdsourced environment.

Professor Ozdaglar’s group also works on developing novel distributed methods that enable collection, storage, and processing of data using large numbers of agents connected through a network. Many of these problems can be formulated as a (coupled) convex optimization problem that needs to be solved by the agents using local information and communication through the network. The standard approach for designing distributed algorithms for such problems uses (sub)gradient-based methods, which suffer from a slow rate of convergence. Her recent work introduced new distributed optimization algorithms with a much faster rate of convergence. In a series of papers with graduate student Ali Makhdoumi, she developed new algorithms for distributed multiagent optimization problems based on the alternating direction method of multipliers (ADMM), which is a classical method for sequentially decomposing optimization problems with coupled constraints. These papers show that ADMM algorithms converge at a faster rate and provide bounds on performance as a function of network structure. In recent work, we have developed new subgradient and ADMM-type algorithms that can be implemented in a distributed manner over directed networks. The key idea of these algorithms is to update estimates at each node based on incoming information while scaling the information of each node by the correct weights such that the graph is "balanced" (i.e., at each node, the amount of incoming information is equal to the amount of outgoing information).

In another project, with Professor Parrilo and postdoctoral associate Mert Gurbuzbalaban, she considers the problem of minimizing the sum of a large number of convex component functions. This problem arises in machine learning problems over large data sets and distributed optimization over networks. Their recent work studies incremental methods for solving such problems that use information about a single component function at each iteration. In particular, this work examines first-order incremental methods and provides new rate guarantees for such methods under smoothness assumptions. We provide lower bounds showing that these methods cannot converge faster than rate 1/k, where k is the number of iterations. We also have developed second-order incremental methods and provided convergence rate results in which condition number dependence is removed. In more recent work, we consider incremental aggregated gradient methods, which process a single component function but keep a memory of the most recent gradients of all component functions to construct an approximation of the full gradient. In contrast with incremental gradient methods, we show that incremental aggregated gradient methods converge linearly. This effort is supported by an Air Force Research Office multidisciplinary university research initiative with the Georgia Institute of Technology and the University of Maryland and by an ONR project with the University of Pennsylvania.

Pablo A. Parrilo

Professor Parrilo (Associate Director of LIDS) 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.

Professor Parrilo, working with PhD student Diego Cifuentes, has initiated research on how structural combinatorial parameters such as treewidth can help to efficiently solve basic questions in computational algebraic geometry (e.g., solving systems of polynomial equations). It is known that chordal structure and bounded treewidth allow for efficient computation in numerical linear algebra, graphical models, constraint satisfaction, and many other areas. We have begun a systematic study of how to exploit chordal structure in computational algebraic geometry, in particular for solving polynomial systems. The structure of a system of polynomial equations can be described in terms of a graph. By carefully exploiting the properties of this graph (in particular, its chordal completions), more efficient algorithms can be developed. To this end we have developed a new technique, which we refer to as chordal elimination, that relies on elimination theory and Grobner bases. By maintaining graph structure throughout the process, chordal elimination can outperform standard Grobner basis algorithms in many cases. The reason is that all computations are done on "smaller" rings of a size equal to the treewidth of the graph. In particular, for a restricted class of ideals, computational complexity is linear in the number of variables. Chordal structure arises in many relevant applications, and we have demonstrated the suitability of our methods in examples from graph colorings, cryptography, sensor localization, and differential equations.

In the same vein (also in collaboration with Diego Cifuentes), we have developed an efficient algorithm to compute permanents, mixed discriminants, and hyperdeterminants of structured matrices and multidimensional arrays (tensors). We describe the sparsity structure of an array in terms of a graph, and we assume that its treewidth, denoted as ω, is small. Our algorithm requires $O(n2^{\omega})$ arithmetic operations to compute permanents and $O(n^2+n3^{\omega})$ operations to compute mixed discriminants and hyperdeterminants. We also proved that mixed-volume computation continues to be difficult under bounded treewidth assumptions.

In collaboration with PhD students Hamza Fawzi and James Saunderson, we have outlined a general methodology to produce concise certificates of the nonnegativity of a function on a finite abelian group. The setup is concerned with nonnegative functions on a finite abelian group G that are sparse with respect to the Fourier basis. We establish combinatorial conditions on subsets S and T of Fourier basis elements under which nonnegative functions with Fourier support S are sums of squares of functions with Fourier support T. Our combinatorial condition involves constructing a chordal cover of a Cayley graph related to G and S, with maximal cliques related to T. Our result relies on two main ingredients: the decomposition of sparse positive semidefinite matrices with a chordal sparsity pattern and a simple but key observation exploiting the structure of the Fourier basis elements of G.

This technique has very interesting consequences. In the case of the Boolean hypercube, by constructing a particular chordal cover of the half-cube graph, we prove that any nonnegative quadratic form in n binary variables is a sum of squares of functions of degree at most $\lceil n/2 \rceil$, establishing a conjecture of Laurent. For the case of nonnegative functions of degree d on $\mathbb{Z}N$ (the discrete cycle), by constructing a particular chordal cover of the dth power of the N cycle, we prove that any such function is a sum of squares of functions with at most 3dlog(N/d) nonzero Fourier coefficients. This shows that a certain cyclic polytope in $\mathbb{R}2d$ with N vertices can be expressed as a projection of a section of the cone of psd matrices of size 3dlog(N/d). This construction provides the first explicit family of polytopes in increasing dimensions wherein the semidefinite extension complexity is asymptotically smaller than the linear programming extension complexity.

Professor Parrilo and PhD student Frank Permenter have developed a new method for simplifying semidefinite programs (SDPs) that blends aspects of symmetry reduction with sparsity exploitation. By identifying a subspace of sparse matrices that provably intersects with (but does not necessarily contain) the set of optimal solutions, we both block-diagonalize semidefinite constraints and enhance problem sparsity for many SDPs arising in sums-of-squares optimization. The identified subspace is in analogy with the fixed-point subspace that appears in symmetry reduction, and, as we illustrate, it can be found using efficient combinatorial and linear-programming-based techniques. The effectiveness of the method has been illustrated with several examples.

Yury Polyanskiy

Robert J. Shillman Assistant 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 nonasymptotic characterization of the performance limits of communication systems, non-Shannon information measures, redundant circuits, and probabilistic methods in combinatorics.

Minimum Energy to Send Bits over Rayleigh-Fading Channels

This work investigates the minimum energy required to transmit, with a given reliability, k information bits over a stationary memoryless Rayleigh-fading channel, under the assumption that neither the transmitter nor the receiver has a priori channel state information (CSI). It is well known that the ratio between minimum energy per bit and noise level converges to -1:59dB as k moves to infinity, regardless of whether or not CSI is available at the receiver. This work shows that lack of CSI at the receiver causes a slowdown in the speed of convergence to -1:59dB as k moves to infinity compared to the case of perfect receiver CSI. Specifically, we show that in the no-CSI case, the gap to -1:59dB is proportional to $[(\log k)/k]^{1/3}$, whereas when perfect CSI is available at the receiver, this gap is proportional to $1/\sqrt{k}$. Numerically, we observe that to achieve an energy per bit of -1.5dB in the no-CSI case, one needs to transmit at least 7×10^7 information bits, whereas 6×104 bits suffice for the case of perfect CSI at the receiver. Interestingly, all results (asymptotic and numerical) are unchanged if multiple transmit antennas and/or block fading is assumed. (Wei Yang and Giuseppe Durisi took part in this work.)

Upper Bound on List-Decoding Radius of Binary Codes

Consider the problem of packing Hamming balls of a given relative radius subject to the constraint that they cover any point of the ambient Hamming space with multiplicity at most L. For odd $L \geq 3$, an asymptotic upper bound on the rate of any such packing is proven. The resulting bound improves the best-known bound (attributable to Blinovsky) for rates below a certain threshold. The method is a superposition of the linear programming idea of Ashikhmin and colleagues and a Ramsey-theoretic technique of Blinovsky. As an application, it is shown that for all odd L the slope of the rate-radius tradeoff is zero at zero rate.

Joint Source-Channel Coding with Feedback

This research quantifies the fundamental limits of variable-length transmission of a general (possibly analog) source over a memoryless channel with noiseless feedback, under a distortion constraint. We consider excess distortion, average distortion, and guaranteed distortion (d-semifaithful codes). In contrast to the asymptotic fundamental limit, a general conclusion is that allowing variable-length codes and feedback leads to a sizable improvement in the fundamental delay-distortion tradeoff. (Victoria Kostina and Sergio Verdu took part in this work.)

Strong Data Processing Inequalities in Power-Constrained Gaussian Channels

This work presents strong data processing results for the power-constrained additive Gaussian channel. Explicit bounds on the amount of decrease of mutual information under convolution with Gaussian noise are shown. The analysis leverages the connection between information and estimation and the subsequent estimation-theoretic result of independent interest. It is proved that any random variable for which there exists an almost-optimal (in terms of mean-squared error) linear estimator operating on the Gaussian-corrupted measurement must necessarily be almost Gaussian (in terms of Kolmogorov-Smirnov distance). (Flavio Calmon and Yihong Wu took part in this work.)

Converse and Duality Results for Combinatorial Source-Channel Coding in Binary Hamming Spaces

This research continues the recent work in combinatorial joint source-channel coding. For the special case of a binary source and channel subject to distortion measured by Hamming distance, the lower (converse) bounds on achievable source distortion are improved for all values of channel noise. Operational duality between coding with bandwidth expansion factors ρ and $1/\rho$ is established. Although the exact value of the asymptotic noise-distortion tradeoff curve is unknown (except at $\rho = 1$), some initial results on interrelations between these curves for different values of ρ are shown and lead to statements about monotonicity and continuity in ρ. (Andrew Young took part in this work.)

Mardavij Roozbehani

Principal Research Scientist Roozbehani led several research efforts related to mathematical modeling, optimization, and control for networked systems, with a particular emphasis on robustness analysis and architecture design for energy systems. The long-term goal of his research is to understand the sources of robustness, fragility, and systemic risk in energy, financial, and transportation networks. Funding for his research comes from NSF, the MIT-Masdar Institute Cooperative Program, and the MIT-Skoltech Initiative.

New Results on Exactness of Convex Relaxation Techniques

Quadratically constrained quadratic programs (QCQPs) are an important class of nonconvex optimization problems that arise in practical engineering. They have been extensively studied in the optimization and control theory literature. In the latter literature, the procedure of replacing the original problem with its more tractable Lagrangian relaxation is often referred to as the "S-Procedure." When the relaxation is exact in the sense that the (convex) optimization of the Lagrangian provides an answer to the original problem, the S-Procedure is called lossless. There are limited results on the losslessness of the S-Procedure or the exactness of Lagrangian relaxation techniques for QCQPs, with the most celebrated result attributed to Fradkov and Yakubovic. According to their result, the S-Procedure is lossless when the number of quadratic constraints is less than or equal to two. Recently, we obtained a more general result that subsumes the older result as a special case. The result is that the S-Procedure is lossless when the number of constraints is less than or equal to $2n - 2$, where n is the dimension of the underlying space. This very exciting theoretical breakthrough has important implications in various practical problems in control and operations research.

Fast New Algorithms for Distributed Power Flow Optimization

The design and operation of power systems consists of solving various optimization problems at different time scales and by various agents at different levels of a hierarchy, with different objectives and with access to different types of information. The need for fast distributed algorithms for optimization and control of power systems is omnipresent due to heterogeneity of information, increased system complexity, and increased volatility (due to renewables), which demands a faster response to changes in the system configuration. In collaboration with graduate student Ming Foo, Dr. Roozbehani developed new distributed algorithms for finding feasible operation points in power systems. While the core of the algorithm extends a previous result based on constrained consensus, the novelty is in allowing distributed agents to include critical constraints from their neighbors in their own local optimization problems. While in general this approach can increase the complexity of local subproblems, this is done in such a way as to conform with the recent 2n – 2 result on the exactness of the S-Procedure. Therefore, local subproblems are guaranteed to be convex and can be solved efficiently. This has resulted in significant improvement in the convergence speed of the underlying consensus algorithm.

Systemic Risk

In collaboration with graduate students Georgia Katsargyri and Tuhin Sarkar, Dr. Roozbehani researched several problems related to systemic risk in financial networks, propagation of shocks, and distributed estimation of rare events using abstract models of networks in general. In financial networks, the role of financial instruments and hedging in patterns of interconnection and systemic risk was studied. This work resulted in new insights on how hedging can sometimes increase risk for the system as a whole while it reduces individual risk. This exciting research is ongoing.

Devavrat Shah

Associate Professor Shah and his research group are involved in developing an understanding of complex networks so as to be able to better engineer them. This includes communication networks such as the Internet, networks of statistical dependencies observed in large data sets, and emerging social networks such as Twitter. A salient feature of Shah’s work across this variety of networks is the use of distributed, iterative, or so-called message-passing procedures as operational building blocks in communication networks (e.g., medium access), as efficient information processing tools in statistical networks (e.g., belief propagation), and as behavioral models in social networks (e.g., gossip algorithms). These collective research activities span computer science, electrical engineering, operations research, and management sciences and utilize tools from algorithms, graphs, information theory, Markov chains, optimization, stochastic processes, and queuing theory.

A generic approach to making decisions using data involves first learning a model from data and then using it to make inferences. Graphical models provide succinct, intuitive representations to capture structured uncertainty in data. To make them broadly usable, it is essential to have efficient algorithms for learning them and using them to perform inferences. Over the past several years, Professor Shah has been involved in developing efficient inference algorithms for graphical models. In the past year, he has made advances in the context of learning them.

Learning is the "dual" problem of inference in graphical models. There has been a flurry of activity during the past decade with respect to learning graphical models. Inference using graphical models has long been known to be computationally hard due to its relation to counting and sampling in the theoretical computer science literature. However, learning graphical models from sufficient statistics, although widely believed to be computationally hard, has turned out to be difficult to establish. In recent work, we settled this question. Specifically, the solution involved establishing an unusual "self-reflection" property of the "independent set polytope" for a gradient algorithm in free energy minimization. It is the same property that had earlier helped us design convergent approximations of inference algorithms. This coincidence seems to suggest a deeper fact, which is that entropy might serve a natural barrier function needed for efficient implementation of interior point methods in optimization.

Suvrit Sra

Principal research scientist Suvrit Sra joined the LIDS community in January 2015. His research is divided into three areas: machine learning theory and optimization algorithms, pure and applied mathematics, and big-data systems and applications. Key activities have involved developing scalable algorithms and well-tuned software implementations (publicly available) for both general purpose and specialized problems arising in machine learning, statistics, and more broadly computational science. The broad methodology developed has found applications in areas such as machine learning, computer vision, information retrieval, image processing, astronomical imaging, brain-computer interfaces, finance, insurance, text analysis, and the life sciences. Along with his collaborators, Sra is also currently pursuing applications in finance (time-series analysis) and health care (personalized medicine and intelligent assistants for doctors).

Machine Learning Theory and Optimization Algorithms

This research focuses on the development of mathematical tools for studying "similarity functions" between structured objects such as covariance matrices, images, strings, and even multimodal data (e.g., medical data). The techniques draw from the theory of kernel functions (harmonic analysis on semigroups and on symmetric spaces) as well as from convex geometry and optimization.

Modern data-intensive machine learning problems require parallel and distributed optimization techniques, and Dr. Sra has been working on several new such optimization algorithms for important machine learning mathematical models. He has produced a number of papers on this topic, several of which have already been published. He continues to pursue an active agenda in this area, and several additional works are under preparation.

Pure and Applied Mathematics

Dr. Sra continues his research into a variety of topics from pure and applied mathematics with the goal of building newer connections with applied tasks in data science. The key achievement in this direction is his work on conic geometric optimization on manifolds of positive definite matrices, which establishes a new direction in nonconvex models that can be solved to global optimality. This work has several applications and touches upon ideas from metric geometry, differential geometry, conic optimization, convex analysis, and large-scale optimization.

Related to this work are several smaller lines of research on basic inequalities involving positive definite matrices, an area of study that Dr. Sra continues to pursue given the vast importance of positive definite matrices in modern applications (e.g., semidefinite programming). Another notable achievement was Dr. Sra's solution to Schur polynomial inequality, which had been conjectured in combinatorics by Cuttler and colleagues.

Applications

Dr. Sra has initiated work on financial and health care data. The financial data will be examined with the help of Undergraduate Research Opportunities Program (UROP) and SuperUROP students and, subsequently, graduate students. In the area of health care, work is under way to establish wider and deeper connections.

John Tsitsiklis

Professor Tsitsiklis (Clarence J. LeBel professor of electrical engineering) 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 have focused on developing methodologies, mathematical tools of broad applicability, and computational methods. Motivating applications for recent work have come from domains such as computer networks and social networks.

Resource-Constrained Computer Networks

This research concerns analysis and optimization of resource allocation methods (routing and scheduling) in queuing networks. During the past year, we focused on a classical model in which incoming jobs are dispatched to one of several available servers. While excellent performance can be attained when the dispatcher receives frequent updates on the state of the servers or uses a large memory, performance apparently deteriorates when communications and memory are limited. We have defined a general class of architectures and have initiated an investigation of fundamental limitations on performance as a function of available resources.

Social Networks

We have continued our work on the problem of controlling the spread of an epidemic in a network. In earlier work, we designed a control policy with favorable performance characteristics under certain assumptions on the available budget of curing resources. In recent work, we established a converse result, showing that the budget we had assumed is order optimal if fast extinction of the epidemic is desired.

Education

Professor Tsitsiklis oversaw a second offering, through EdX, of the online 6.041x Introduction to Probability undergraduate class. Furthermore, he integrated the available online materials into the corresponding residential class.

Alan Willsky

Edwin Sibley Webster Professor (retired) Alan Willsky continues to lead the Stochastic Systems Group (SSG), whose research focuses on developing statistical algorithms and methodologies for complex problems of information extraction and analysis from signals, images, and other sources of data. The work extends from basic mathematical theory to specific areas of application. Funding for this research currently comes from the Air Force Research Office.

Research in SSG principally focuses on exploring rich classes of stochastic models for complex phenomena and, in particular, on developing computationally efficient and scalable algorithms for inference and data fusion and new methodologies for learning models. Our work has addressed two distinct classes of models, namely so-called graphical models and hierarchical Bayesian nonparametric models for dynamic phenomena. In the case of graphical models, we have recently completed (and are currently documenting) a new methodology for learning models on graphs with a small number of hidden variables that capture global correlations in large sets of observed variables and, hence, may be densely connected to all of the observed nodes in the graph. This allows the graphical connections among the observed nodes to have a very simple form, namely through a cycle-free graph (i.e., a tree). We had previously shown that such models involve very efficient inference algorithms, and in the past year we extended this investigation to produce highly distributed, parallel algorithms to perform that inference. Our work on learning such models also has led to a very efficient algorithm, and we have demonstrated experimentally that we can learn very accurate models for quite complex data (e.g., travel delay data across the United States). Continuing work involves new convex-optimization-based methods for learning hierarchical or multiresolution models. A major problem has been developing methods that can learn models of this type when neither the structure of the hierarchical tree (i.e., which nodes at one level of the hierarchy are connected to which nodes at the levels both immediately above and below) nor the dimensions of variables are known. This is a highly challenging problem that is ill posed unless one includes, in some manner, the aim to have models in which the dimensions of the variables are small. Our recent breakthrough has led to a new method that successfully addresses this challenge, and we are currently working on implementing and demonstrating the power of our new method. Our research on graphical models has numerous applications, such as in remote sensing data assimilation and computer vision.

Our work on Bayesian nonparametric methods for discovering complex behaviors in temporal or spatiotemporal data has focused on developing models that can automatically learn behaviors that may “switch” among an unknown number of dynamic behaviors (where each of those behaviors also needs to be learned). This involves including hidden variables (of unknown cardinality) capturing the switching among these modes and learning the dynamics of this switching behavior—in our case, using semi-Markov models—as well as the nature of the dynamics corresponding to each of the modes. Several of our applications have provided the drivers for this work, namely power disaggregation (i.e., automatically decomposing the power consumption signal from, for example, a home in order to determine what power sources are being used and when each is used), learning the motion behavior of mice, and analyzing speech signals. A significant challenge in developing algorithms of this type that can deal with massive data sets is that of scalability to large data sets. We have successfully addressed this challenge through several advances, the first of which involves a new method for dealing with so-called transition time distributions for our hidden semi-Markov models. Using such models has substantial power over the use of standard hidden Markov models (indeed, power that is absolutely needed for the applications we have mentioned), but that power comes at the apparent expense of sacrificing the computational efficiency of Markov models. We have overcome this by exploiting the structure of a very rich class of transition distributions (namely so-called negative binomial distributions) in order to produce algorithms that are only modestly more complex than those used in Markov models. The second advance has been the development of variational methods for our new models, allowing for the assimilation of very large data sets.

Moe Win

The Wireless Communication and Network Sciences Laboratory, led by Professor 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 for hosting students from both UROP and the MIT Summer Research Program. The group recently hosted a visiting female graduate student and two undergraduate students as summer research interns. 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 University of Lund in Sweden; the University of Oulu in Finland; the Singapore University of Technology and Design and Nanyang Technological University in Singapore; Tsinghua University in China; Kyung Hee University in Korea; Draper Laboratory; the Jet Propulsion Laboratory; and Mitsubishi Electric Research Laboratories.

Current research topics include network localization and navigation, network interference exploitation, intrinsic wireless secrecy, adaptive diversity techniques, and ultra-wide-bandwidth systems. Details of a few specific projects are provided below.

Network Localization and Navigation

The group has continued its research on network localization and navigation, in particular deriving a tractable wideband ranging model and developing efficient resource allocation algorithms for network localization and navigation. The group has derived a mathematical model that describes ranging information as a function of wireless environment, signal features, and energy detection techniques. Based on the proposed range information model, the group has developed low-complexity ranging algorithms for soft-decision and hard-decision localization. Sample-level simulations show that soft-decision localization can significantly outperform hard-decision localization. The group has also established an optimization framework for robust resource allocation in cooperative localization and navigation with the goal of minimizing localization errors in the presence of network parameter uncertainty and resource constraints. Efficient centralized and distributed resource allocation strategies are obtained via conic optimization. These strategies lead to energy-efficient network navigation algorithms that significantly improve localization accuracy. These results provide guidelines for the operations of energy-efficient localization and navigation networks.

Intrinsic Network Secrecy

The group has also devoted effort to studying how physical-layer security can strengthen secrecy of communications by exploiting intrinsic properties of communication channels and by engineering network interference. First, the group has advanced its proposed theoretical framework that analyzes the benefits of various interference engineering techniques for network secrecy. Second, the group has introduced the concept of cognitive network secrecy and analyzed secrecy performance in such a context. The analysis reveals that while interference is usually considered deleterious for communications, mutual interference between primary and secondary networks can be beneficial for cognitive network secrecy. Based on this observation, interference engineering strategies have been proposed to enhance cognitive network secrecy. Finally, the group has introduced the notion of multitier network secrecy and analyzed how interference engineering techniques with different computation and communication overhead benefit network secrecy protection in multitier networks. The group’s insights on how interference engineering techniques benefit wireless network secrecy will guide the design of such techniques for a new level of communication confidentiality.

Highlights, Awards, and Events

The laboratory continues to organize the broadly attended LIDS seminar series and the LIDS student conference, which is organized solely by LIDS students and provides an interactive forum to discuss their research. LIDS produces a community-oriented magazine, *LIDS|ALL*, which continues to receive great praise. *LIDS|ALL* includes articles on important events related to LIDS and profiles of individuals whose lives have been shaped by LIDS in significant ways. LIDS has recently launched a new website with enhanced content and design.

LIDS faculty continue to be involved in the organization of major workshops and conferences, including the 21st Century Statistics Workshop held at MIT in May (co-organized by Professor Dahleh), the Institute for Pure & Applied Mathematics summer school on games and contracts for cyber-physical security (co-organized by Professor Ozdaglar), and workshops on analysis and control of network dynamics (co-organized by Professor Ozdaglar), optimization and parsimonious modeling (co-organized by Professor Parrilo), and graphical models, statistical inference, and algorithms (co-organized by Professor Shah).

Finally, LIDS faculty, students, and alumni continue to receive substantial recognition for their contributions, with numerous national and international awards and honors. Some notable examples are listed below.

Awards

- Dimitri Bertsekas was the 2014 winner of the INFORMS (Institute for Operations Research and the Management Sciences) Optimization Society Khachiyan Prize. Also, Professor Bertsekas was the 2015 winner of the George B. Dantzig Prize from the Society for Industrial and Applied Mathematics and the Mathematical Programming Society.
- Professors Kostas Bimpikis (Stanford) and Ozan Candogan (Duke), both LIDS alums, and graduate student Kimon Drakopoulos were members of one of the winning teams in the 2014 LinkedIn Economic Graph Challenge.
- Graduate student Kimon Drakopoulos received the Sloan Outstanding Teaching Assistant Award for 2014–2015.
- Jonathan How received the American Institute of Aeronautics and Astronautics (AIAA) Intelligent Systems Best Paper Award at the AIAA Infotech@Aerospace Conference.
- Sertac Karaman received an Army Research Office Young Investigator Award in May 2015.
- Sanjoy Mitter received the 2015 Eric E. Sumner Award from the Institute of Electrical and Electronics Engineers (IEEE).
- LIDS student Marzieh Parandehgheibi was named a 2015 Graduate Woman of Excellence by the Office of the Dean for Graduate Education. She is supervised by Professor Modiano.
- Devavrat Shah received the Distinguished Young Alumni Award from IIT Bombay in March 2015.
- LIDS alum Jinwoo Shin won the 2015 Association for Computing Machinery (ACM) SIGMETRICS (Special Interest Group for the Computer Systems Performance Evaluation Community) Rising Star Research Award. He was supervised by Professor Shah.
- John Tsitsiklis received the 2015 EECS Louis D. Smullin Award for Teaching Excellence.
- LIDS alum Kush Varshney won the Best Social Good Paper award at the 20th ACM SIGKDD (Special Interest Group on Knowledge Discovery and Data Mining) Conference on Knowledge Discovery and Data Mining. He was supervised by Professor Willsky. Varshney also received the 2014 IBM Faculty Award.

- Alan Willsky received the 2013 IEEE Signal Processing Society Award (announced in May 2014). (Note that Professor Willsky's receipt of this award was not mentioned in the 2014 LIDS report to the president as it should have been.)
- Moe Win received the 2014 IEEE SPCE (Signal Processing and Communications Electronics) Technical Recognition Award from the IEEE ComSoc Signal Processing and Communications Electronics Technical Committee for "his continuous and outstanding contributions to the technological advancement of signal processing for communications."
- Kuang Xu was one of the recipients of the 2014 Dimitris N. Chorafas Foundation Award. He was supervised by Professor Tsitsiklis.
- MEng student Kang Zhang received the David Adler Memorial EE MEng Thesis Award.

Honors

- Munther Dahleh was named the inaugural director of the Institute for Data, Systems, and Society.
- Jonathan How was named editor-in-chief of IEEE Control Systems Magazine and director of the Ford-MIT Alliance. Also, he was appointed to the US Air Force Scientific Advisory Board.
- Sanjoy Mitter was elected an International Federation of Automatic Control Fellow in June 2015.
- Eytan Modiano was selected to serve on the IEEE Fellows Committee.
- Asuman Ozdaglar was named director of LIDS. She was also named associate director of the Institute for Data, Systems, and Society.
- Suvrit Sra continued to cochair the Neural Information Processing Systems Workshop on Optimization for Machine Learning.
- LIDS alum Kush Varshney was selected by the National Academy of Engineering to participate in the Frontiers of Engineering Symposium. Varshney also was a finalist for the 2014 Bell Labs Prize.

Future Outlook

LIDS continues to be an international center of excellence and a leader in the science of information and decision systems. We are excited to be part of IDSS, which brings statistics and domain expertise and whose charter aligns with the LIDS style of research, in which fundamental challenges are addressed in a systematic and rigorous manner. Many of the LIDS faculty play active roles in defining the intellectual agenda, designing new academic programs in statistics and social and engineering systems, and directly leading the search for new faculty in networks and statistics. The ambitious interdisciplinary remit of IDSS will offer new opportunities and challenges for faculty, researchers, and students at LIDS. New research in fields as diverse as energy, transportation, social networks, health care, and financial systems—fields involving the type of rigorous quantitative work that has always been the hallmark of LIDS—can now be combined with vast quantities of relevant data and detailed knowledge of relevant institutions and practices. With the addition of new faculty and researchers and interactions with a number of world-leading researchers we are planning to host this year, we expect LIDS activities to continue to grow and expand in 2015–2016 and anticipate that LIDS will play a leadership role in defining and addressing important societal problems both within IDSS and in the broader global community.

Asu Ozdaglar
Director (effective October 1, 2014)
Professor of Electrical Engineering and Computer Science

Munther A. Dahleh
Acting Director (through September 30, 2014)
Professor of Electrical Engineering and Computer Science

Pablo Parrilo
Associate Director
Professor of Electrical Engineering and Computer Science