Collective Phenomena in Complex Networks

Ali Jadbabaie

JR East Professor of Engineering

Associate Director, Institute for Data, Systems, and Society

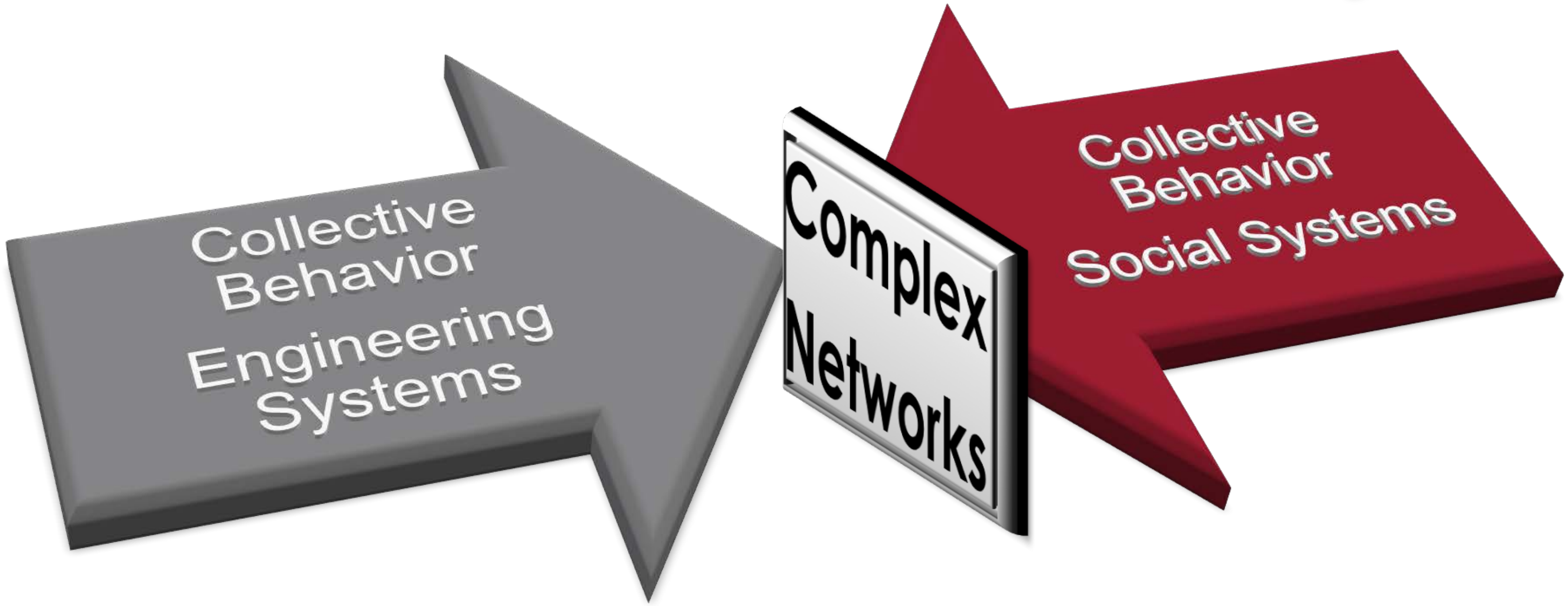
Director, Sociotechnical Systems Research Center

http://web.mit.edu/~jadbabai/www

IDSS MIT INSTITUTE FOR DATA, SYSTEMS, AND SOCIETY LIDS MIT Civil and Environmental Engineering

Research supported by DARPA, ARO, ONR, AFOSR, NSF, and Office of Secretary of Defense

Research Summary:



Flocking & Motion Coordination	**Social Learning**
Synchronization, Consensus	**Opinion Dynamics**
Optimization for Machine Learning	**Controlling Epidemics**

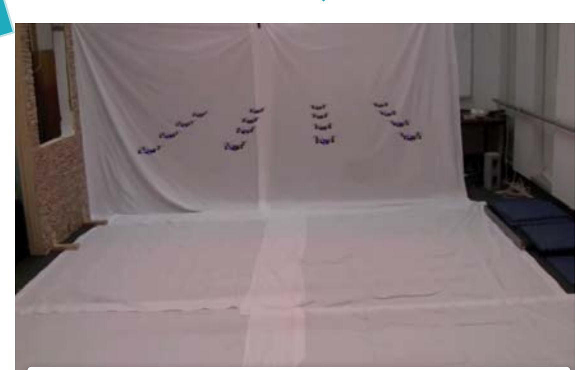
Tools: Network Science, Systems Theory, Dynamics and Control

Domains: Autonomy, Sensor & Infrastructure Networks, Social Phenomena and Social Behavior

From Single to Multi-agent Systems

Complexity of dynamics

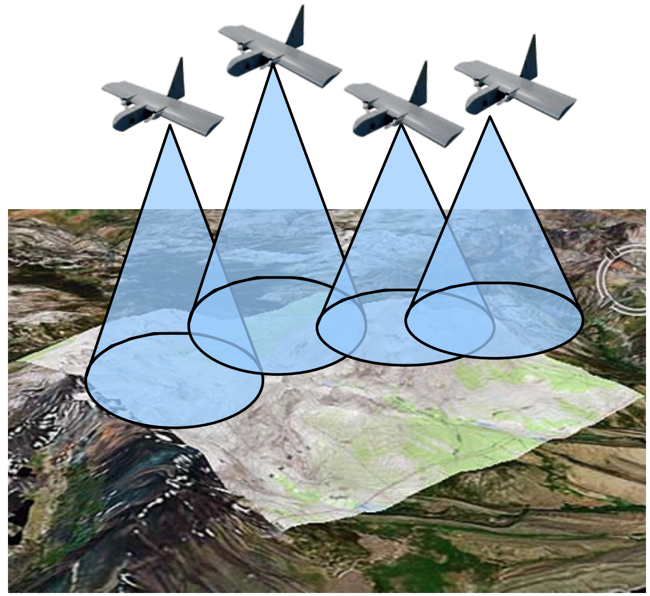
Single agent, circa 2001
Optimization-based control

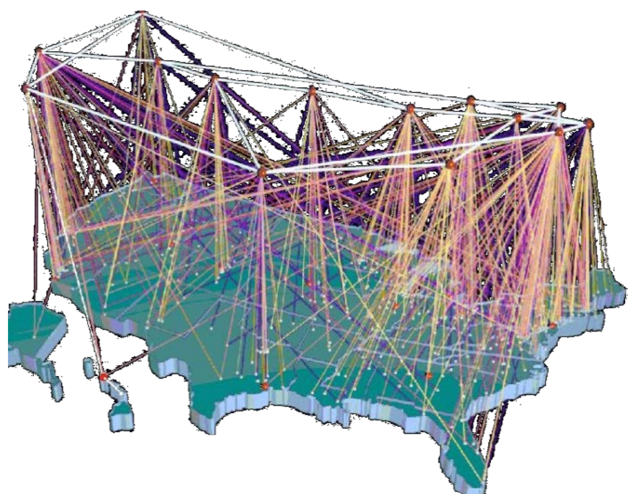


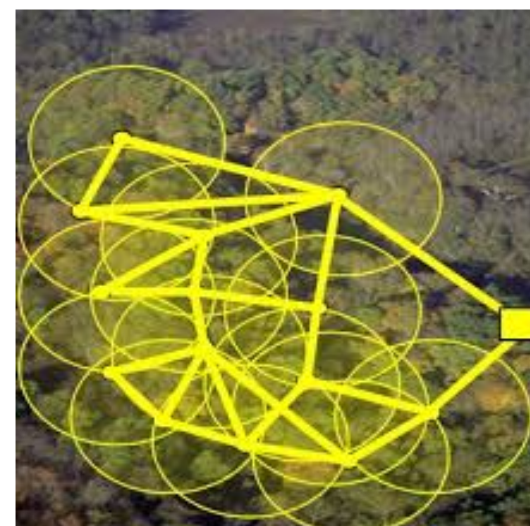
multi-agent, circa 2012,
Melinger, Kushliev, Kumar

Complexity of interconnection

Collective Behavior: Autonomous Systems

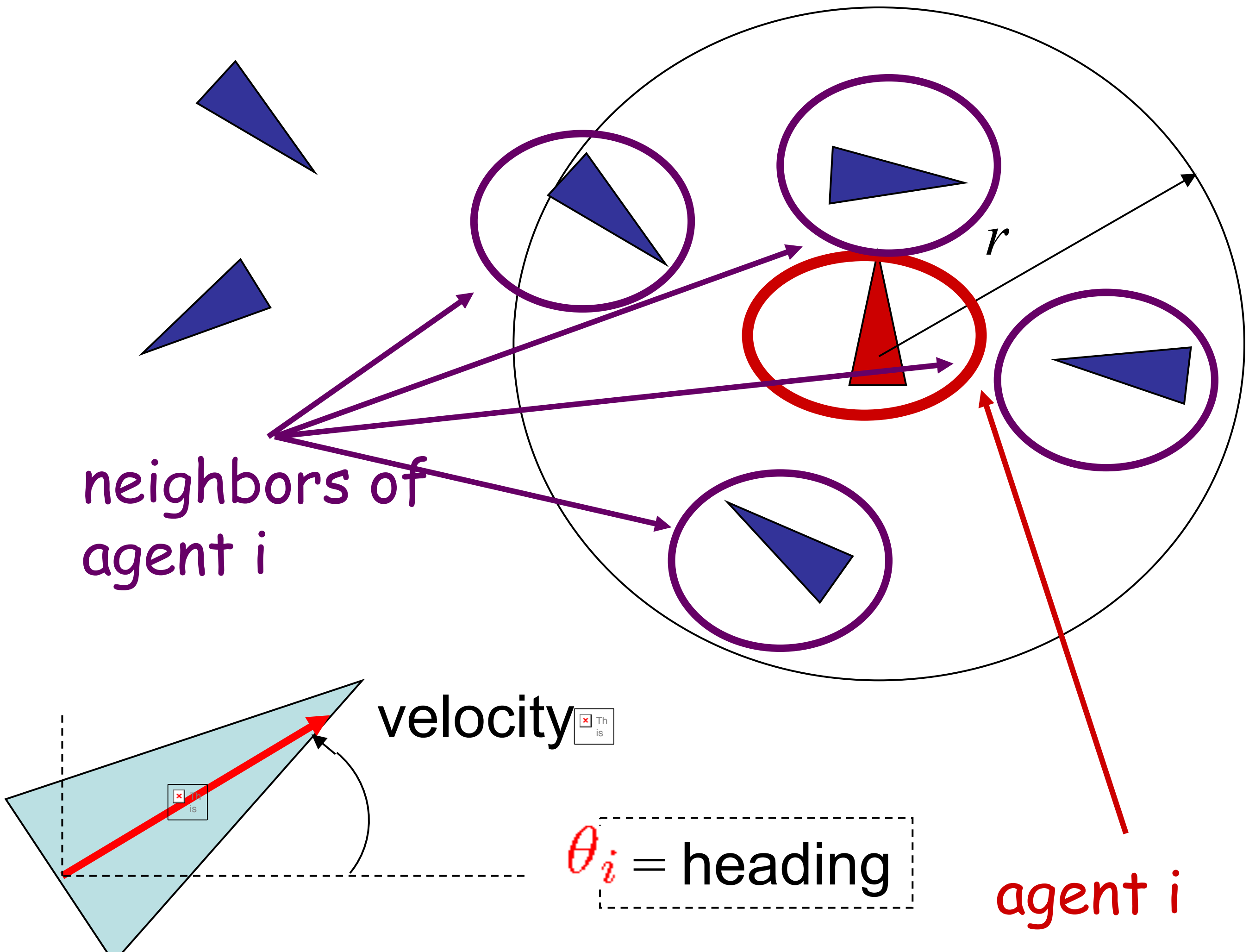


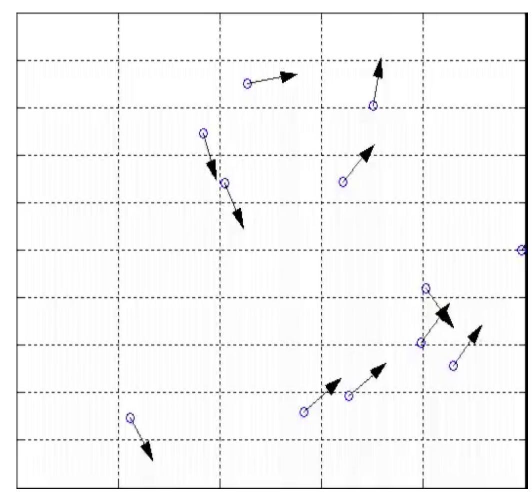




A Kinematic Model of Flocking: Vicsek ‘95

`Average’ heading of each agent and its neighbors, move one step



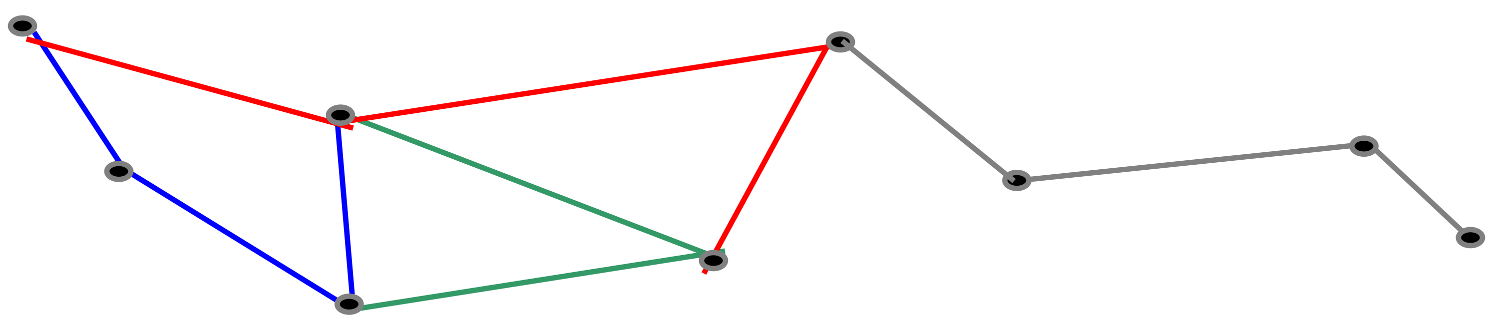


Conditions for Coordination

Difficulty: motion changes the network, and the network affects the motion

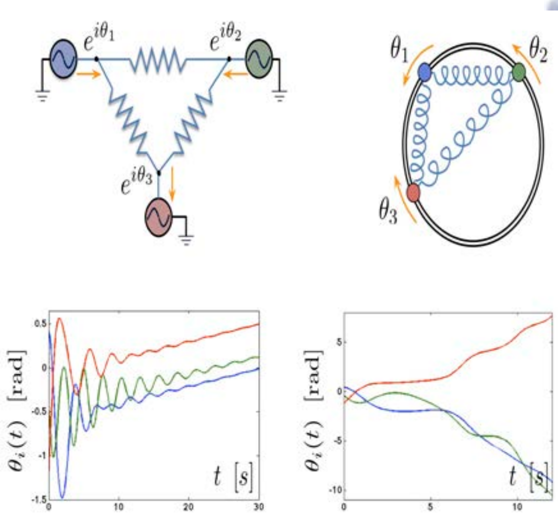
Theorem (Jadbabaie et al. 2003) *if sequence of graphs jointly connected , then all agents will asymptotically flock together.*

- Extensions to dynamic models, leader-follower and other formations, nonlinear dynamics, heterogeneous time delays, random networks,….
- Long history in parallel & distributed computation (Tsitsiklis '84, Seneta 77,81)
- Applications to: distributed optimization, statistics and inference, , control, robotics, signal processing, opinion dynamics, social networks, gossip algorithms



Jadbabaie, Lin, Morse, 2003, Tahbaz-Salehi and Jadbabaie 2007, 2010, Fazeli and Jadbabaie 2012-13

Synchronization in Complex Networks



$$\frac{d\theta_i}{dt} = \omega_i + \frac{K}{N}\sum_{j=1}^{N} A_{ij}\sin(\theta_j - \theta_i)$$

Kuramoto, ‘1975

- Swing equations in the grid
- Flashing fire flies
- Mexican waves
- Rhythmic applause
- Pacemaker cells & neurons

- Effect of network structure?
- Frequency mismatch?
- Onset of synchronization?
- Stability of synchronous state

Jadbabaie, Motee, Barahona, 2004, Jadbabaie, Papachristodoou, 2005,2009

Multi-agent Autonomous Platooning:

Sabau & Jadbabaie 2015-17

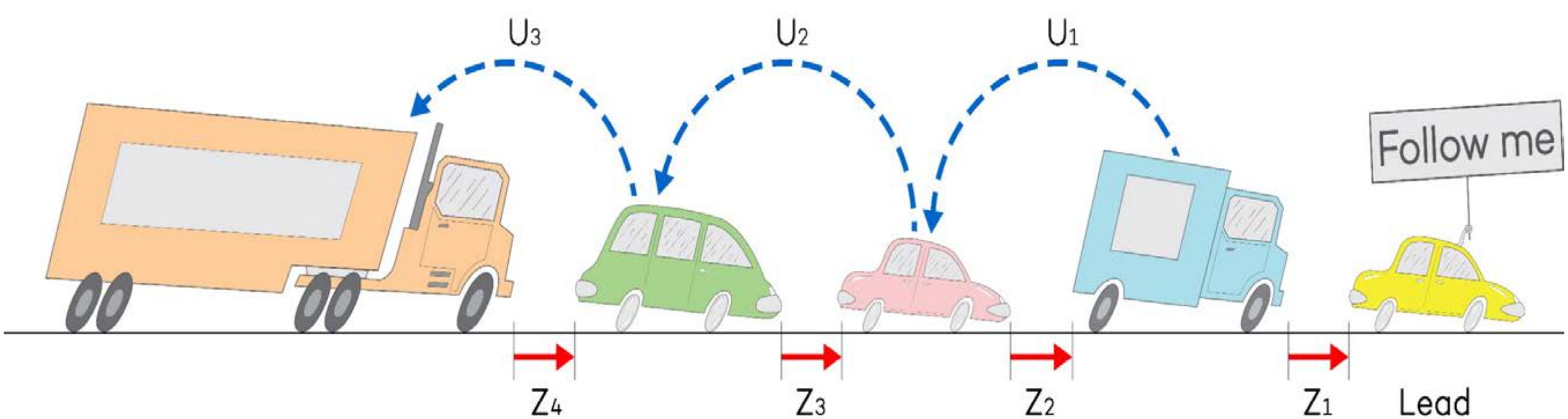
Can follow an uncooperative leader

Robust to presence of road disturbances

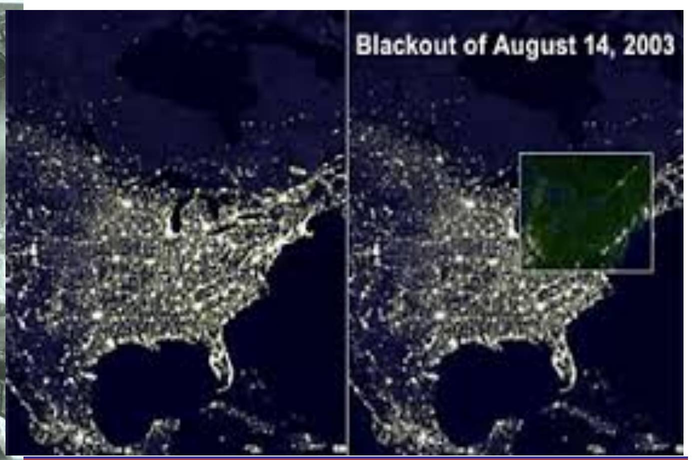
Guaranteed collision-free performance.

Eliminates the ``accordion" effect (string instability)

Compensate for Vehicle to Vehicle delays

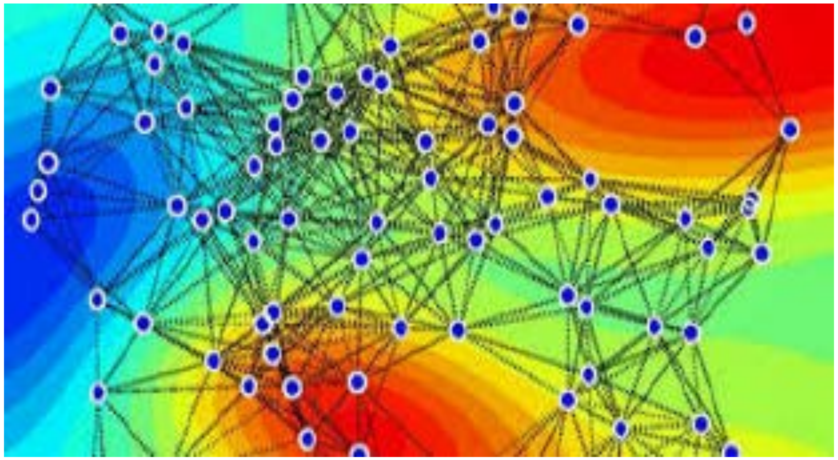


Collective Behavior in Social Systems: Opinion Aggregation, Collective action, and Cascades



Cascading failures: Why do shocks result in cascades?
How to intervene to maximize/minimize the spread?
What is the role of network structure? Popcorns vs dominos?

Social Learning and Distributed Inference



- How to combine opinions of peers (or sensor measurements) and observations to *learn* an unknown state?

- How does the network structure affect learning?

Jadbabaie et al. 2012,13, Molavi et al. 2015, Shahramour et al. 2015

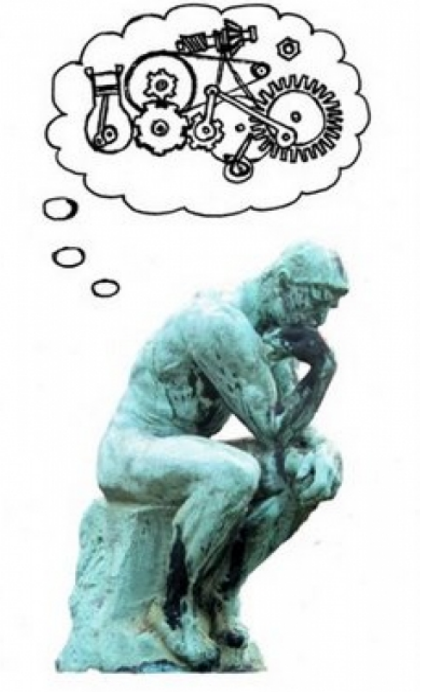
Social Learning and Opinion Pooling

- Opinions of individuals often influenced by private observations and opinion of friends, neighbors, …
- How to combine private observations and peer opinions?

Jadbabaie et al. 2012, 2013, Rahimian et al 2015, Khan & Jadbabaie 2016

Rational vs. Rule of Thumb Learning Rules

- How to combine private observations and peer opinions?
  - Bayesian *Acemoglu et al. 2011, 2016, Mossel & Tamuz (2015)*
  - Non Bayesian: *DeGroot'74, Golub & Jackson 2010, Jadbabaie et al. 2012-14*



- Model how cognitive burden of Bayesian updating can lead to adhoc, rule of thumb rules

Social Learning & Rational Inference

Bayesian updating in networks: too much of a cognitive burden

Major departure: Imperfect Recall

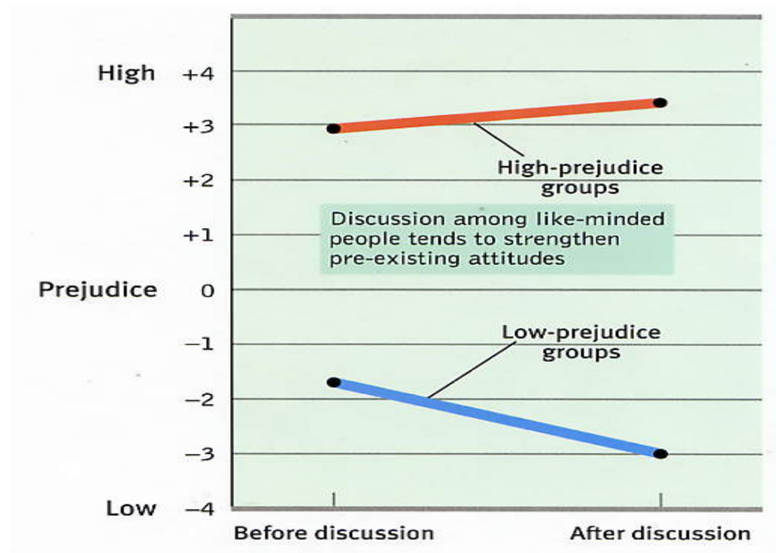
Take neighbors beliefs as sufficient statistic of what they know

$$\mu_{it+1} = \mathrm{BU}\big(f_i(\mu_i^t); \omega_{it+1}\big), \; \mu_i^t = (\mu_{jt})_{j \in N_i},$$

- What properties should f_i have for learning to occur?
- How does the network structure affect learning?
- f_i can be linear, log-linear, but cannot have too much " logarithmic curvature"

Group Polarization and Learning

- Group Polarization: Tendency to shift to more extreme opinions after group discussion



Theorem (*Molavi, Tahbaz-Salehi, Jadbabaie 2016*) : *Networked societies Subject to imperfect recall, learn if and only if opinions are non-polarizing. Learning is non-generic, "knife-edge" and fragile.*

Rational Decision Making in Organizations

- Experts/professional committees
- Examining witness testimonials
- Congressional debates
- Jury deliberations
- Medical diagnoses

Controlling Epidemics

Brockmann D, Helbing D. The hidden geometry of complex, network-driven contagion phenomena. Science. 2013.;342(6164):1337-42.

- How to stop Epidemics with limited resources?
- How to maximize spread of ideas/products ?
- What is the effect of network structure?

Controlling Epidemics in Networks

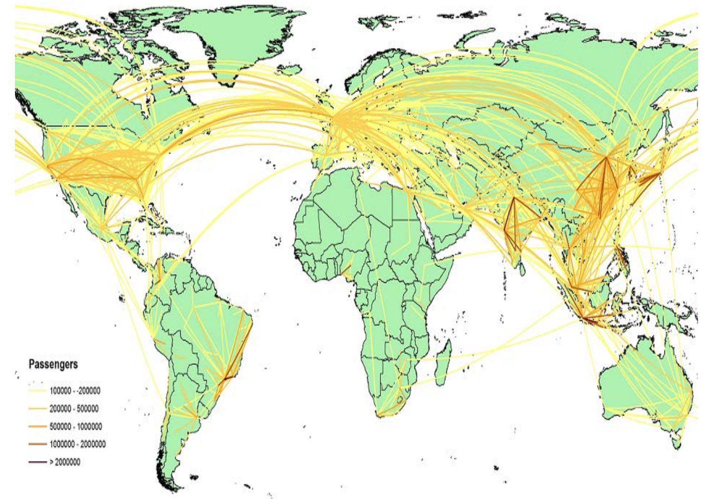
Key Question – how to optimally intervene to stop or maximize contagion ?

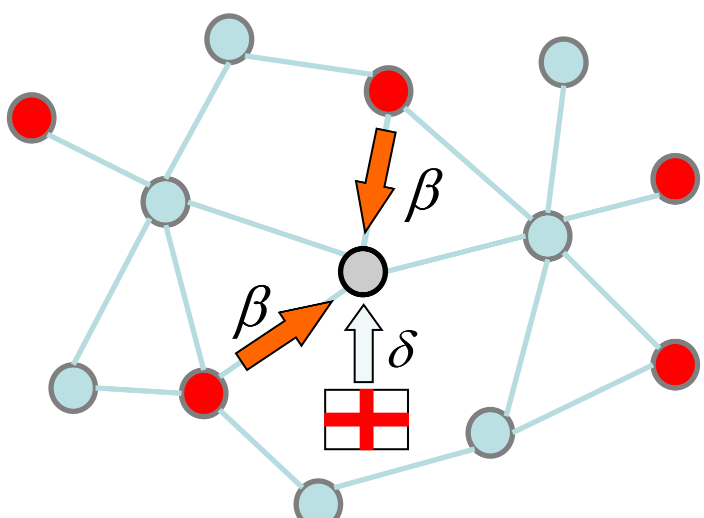
Existing control results:

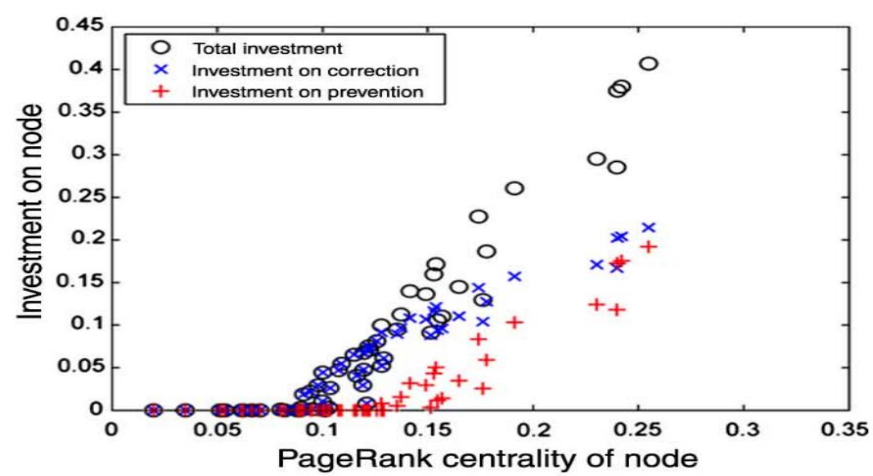
- Centrality-based measures
- Greedy heuristics

Our approach: Geometric Programing

- Directed, weighted graphs
- Heterogeneous agents







Enyioha et al. 2015, Preciado et al. 2014

Maximizing Spread: Quality or seeding ?

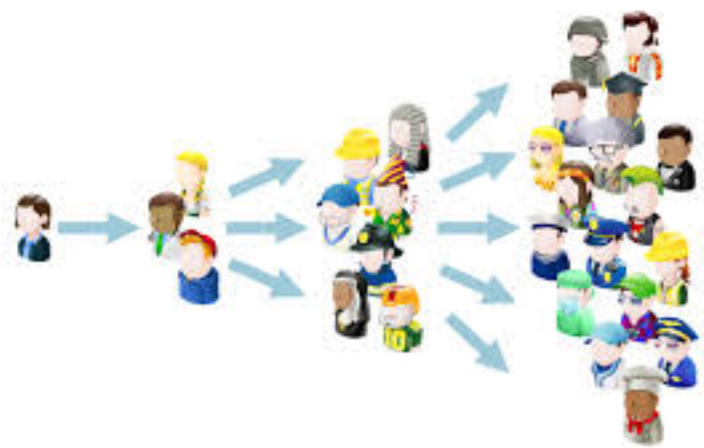
- Two parties compete for minds/ideas/market share in a network
  - Can "seed" a few initial infections (via persuasion, incentives, etc.)
  - Can invest in quality of product/message
  - parties have limited budget. Invest in quality or seeding?
- Subsequent contagion propagated via the network
- What happens when strategic firms play? s there an equilibrium? What role does structure play?

Fazeli,Ajorlou, Jadbabaie, 2015

Maximizing Spread: Word of Mouth

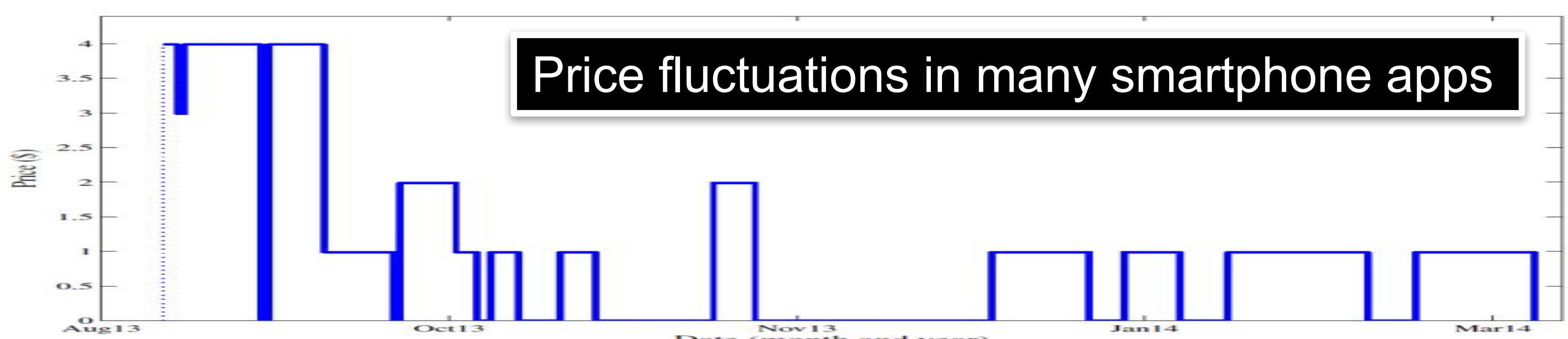
How to spread a product/idea in a large network?

Strategic Agents: Adopt the new technology when the price is right, and enough friends adopt

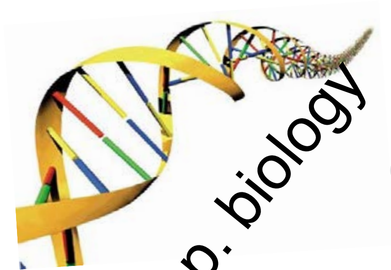


- If priced too low, many adopt, but no profit
- If priced too high, limited spread

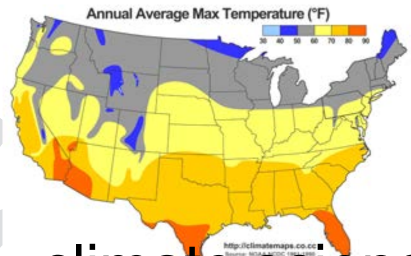
Theorem: Periodically sell at cost



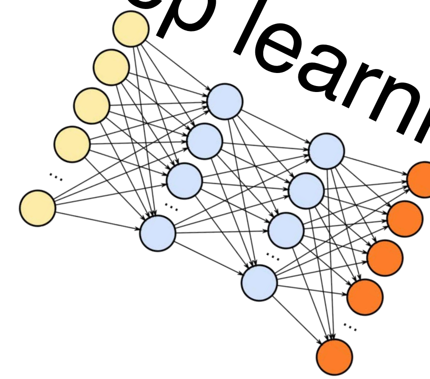
optimization for ML: fundamental limits



comp. biology



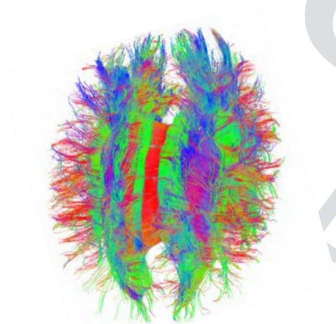
climate science



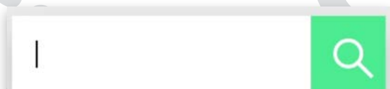
deep learning

Nonconvexity

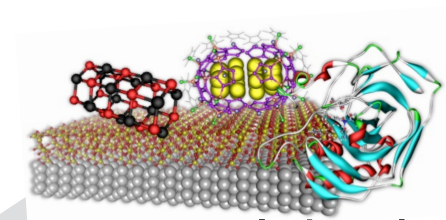
Decentraliz



medical imaging

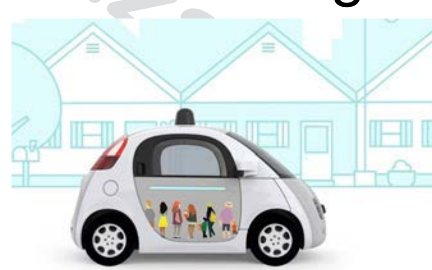


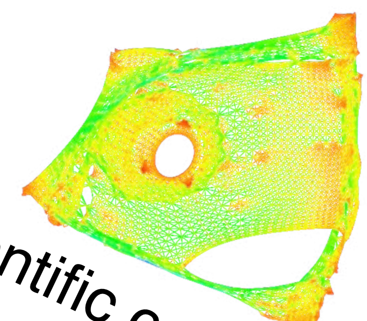
semantic search



comp. material science

self-driving cars





scientific computing

Non-convex, incremental, distributed, second order methods

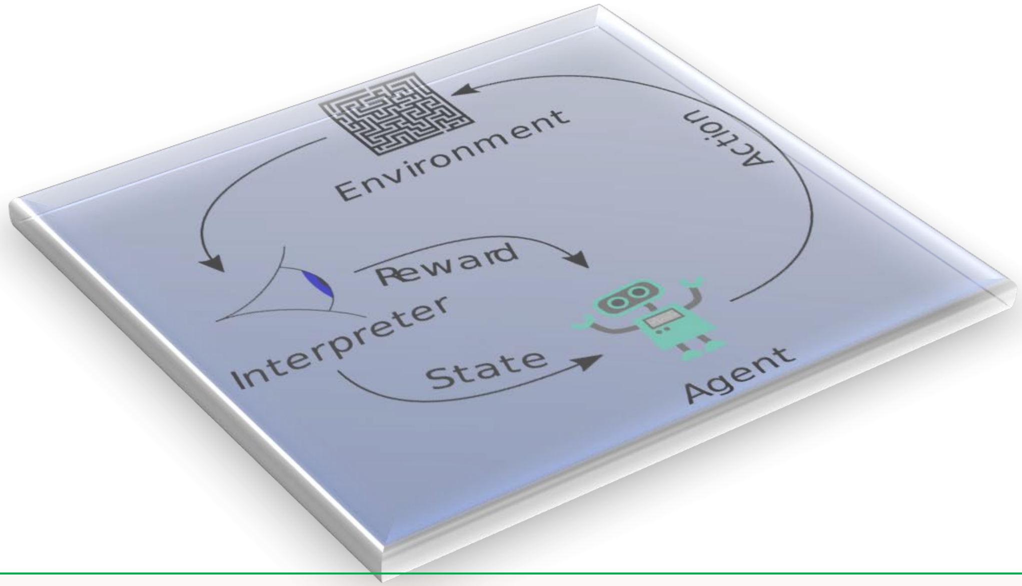
Empirical Risk Minimization and Online Learning

$$\min_{x \in \mathcal{M}} \quad \mathbb{E}[F(x, \xi)]$$

$$\min_{x \in \mathcal{M}} \quad \frac{1}{n} \sum_i f_i(x)$$

Optimizing Empirical Risk for deep neural networks

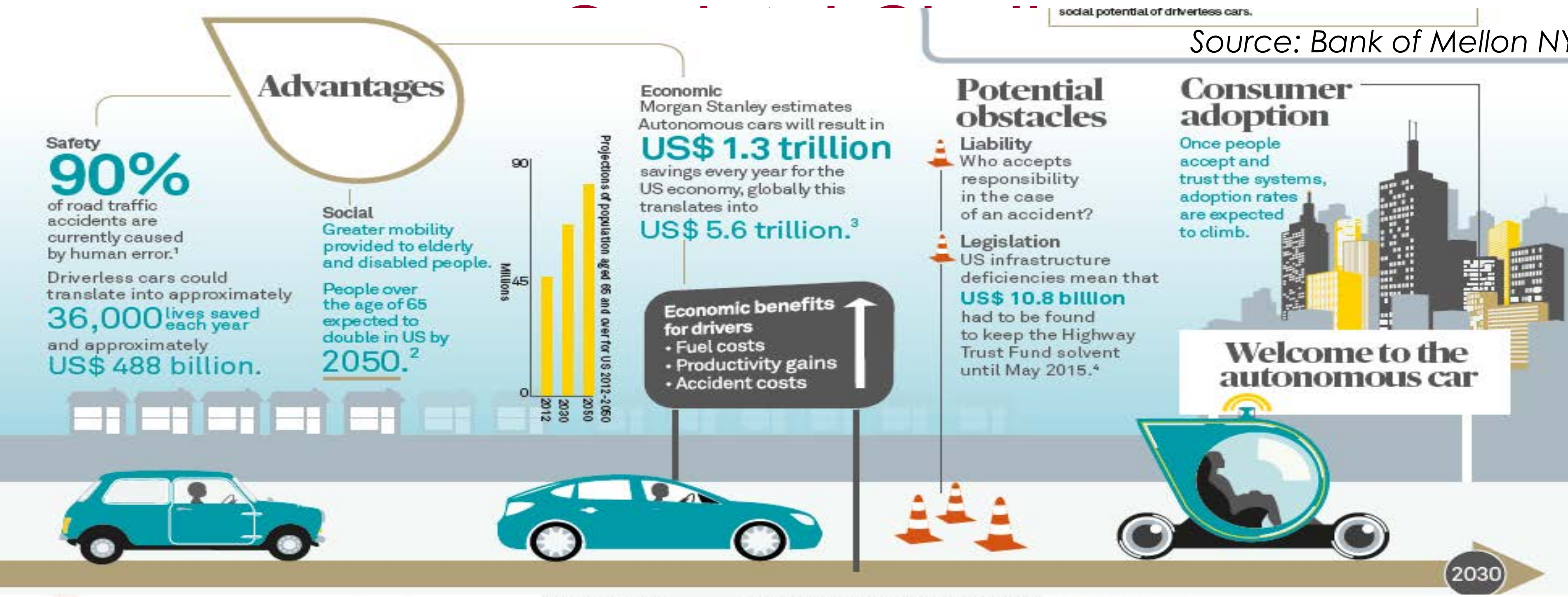
Yun, Sra, Jadbabaie (2018)



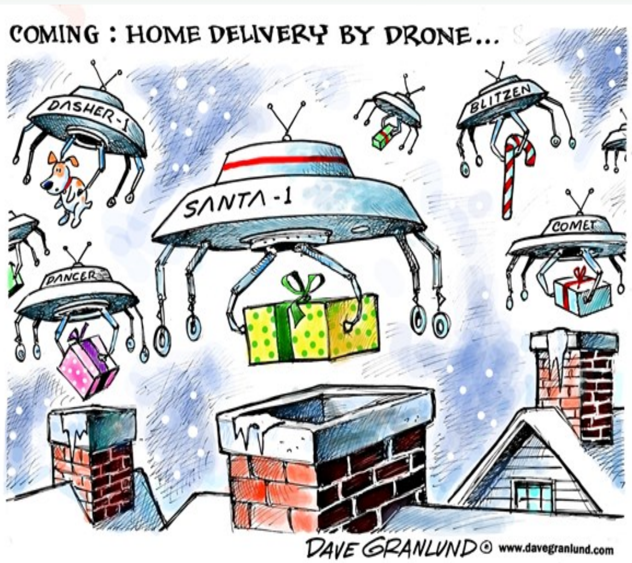
General online protocol:

- Observe some side information
- Make a prediction / decision
- Observe data/outcome (or some partial information)
- Adjust the model

Autonomous Transportation + Urbanization

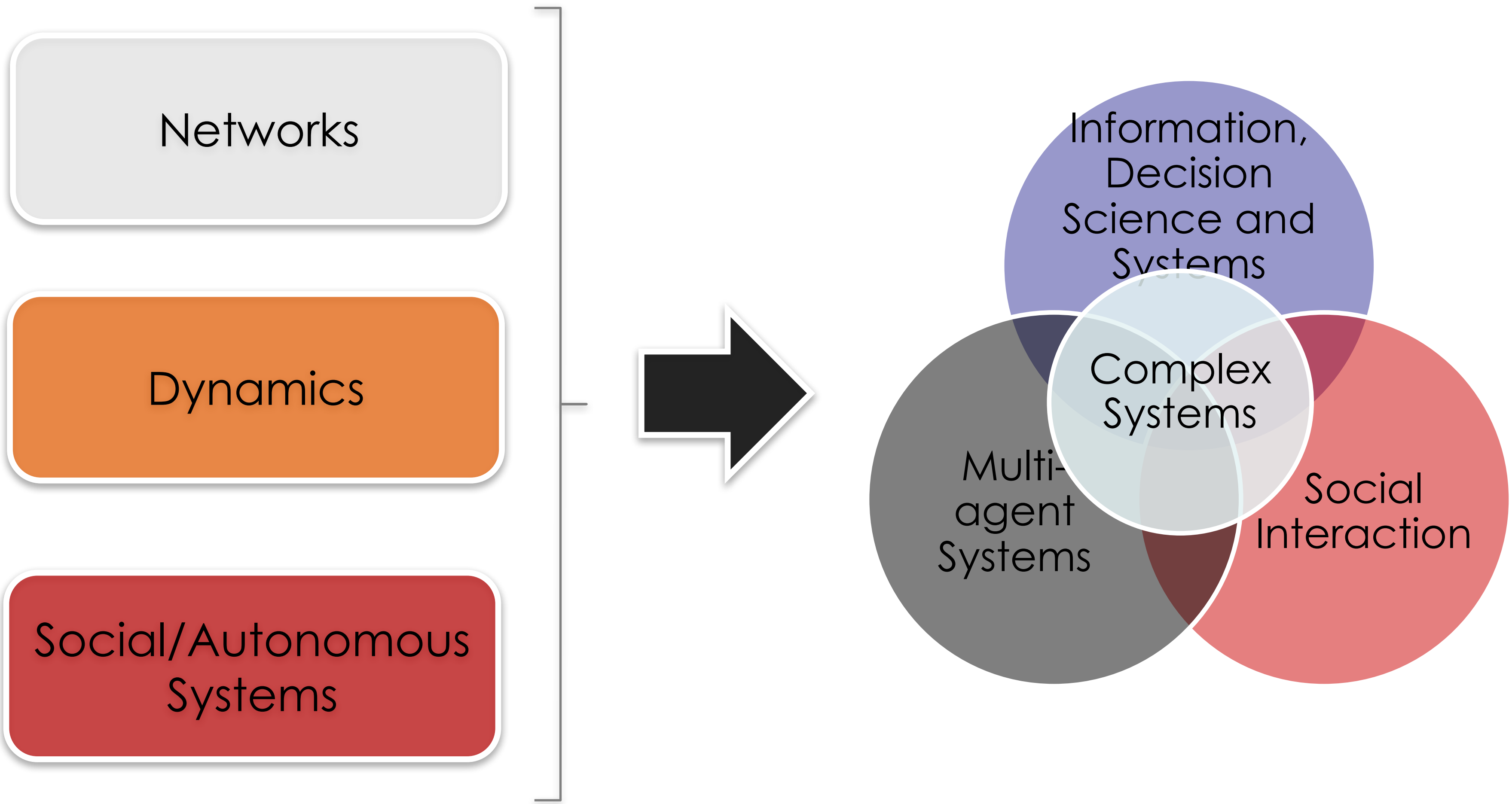


ociety. 18 December 2013.
January 2015.
4 Source: "House Approves Highway Trust Fund patch," CBS
http://www.cbsnews.com/news/house-approves-highway
5 Investment Managers are appointed by BNY Mellon Invest
EMEA Limited ("BNYMIM EMEA") or affiliated fund operati
undertake portfolio management activities in relation to co
and services entered into by clients with BNYMIM EMEA or



Social Behavior of drivers,
Institutional behavior
Of markets/regulators

Summary


Networks
Dynamics
Social/Autonomous Systems
Information, Decision Science and Systems
Complex Systems
Multi-agent Systems
Social Interaction

MIT INSTITUTE FOR DATA, SYSTEMS, AND SOCIETY

IDSS

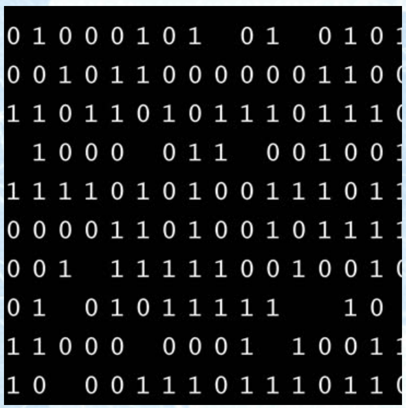
January, 2018

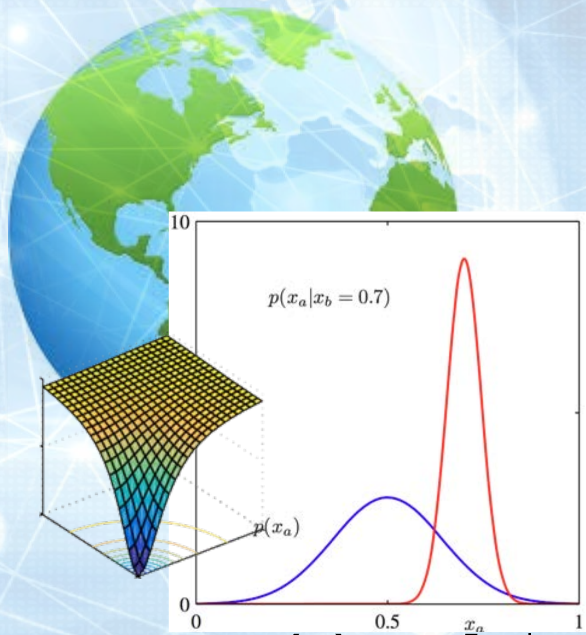
Our society depends on ***massively complex, data-rich systems.*** Increasingly, the answers to society's most serious challenges lie in ***the ability to extract from these systems and vast data sets new patterns, new pathways, and new solutions.***

- MIT President Rafael Reif

IDSS

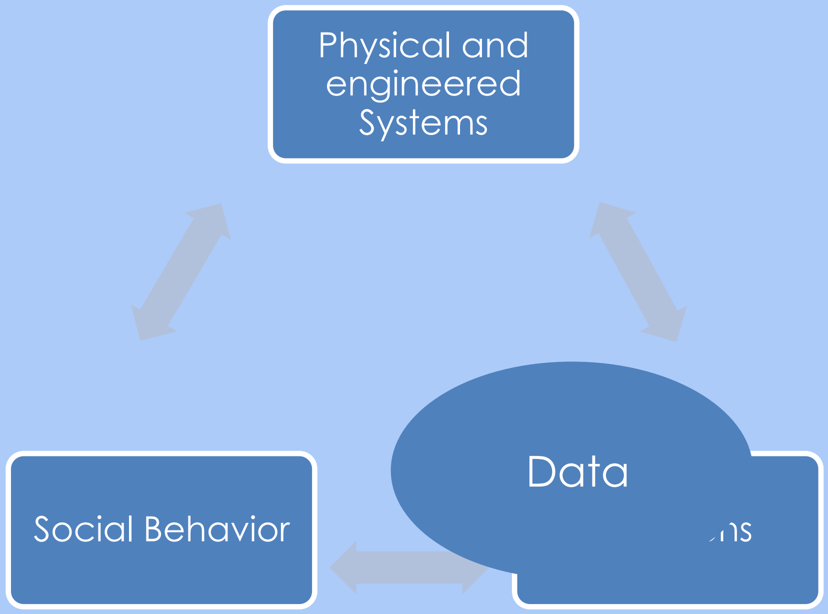
Data to Models to Decisions





$$m_{\pi*}(x) = E_\pi[\mu_i | X_i = x],$$

*"Addressing **complex societal challenges** by advancing education and research at the intersection of **statistics**, **data science**, **information and decision systems**, and **social sciences**."*



MULTI-DISCIPLINARY RESEARCH THAT ADDRESSES COMPLEX SOCIETAL CHALLENGES

Tackling Complex Problems in key Application Domains

- Autonomous Systems
- Energy
- Environment
- Finance
- Health Care
- Infrastructure
- Social Networks

+

Analytical Expertise

- Statistics & data science
- Information & decision theory
- Understanding human and institutional behavior (social sciences)

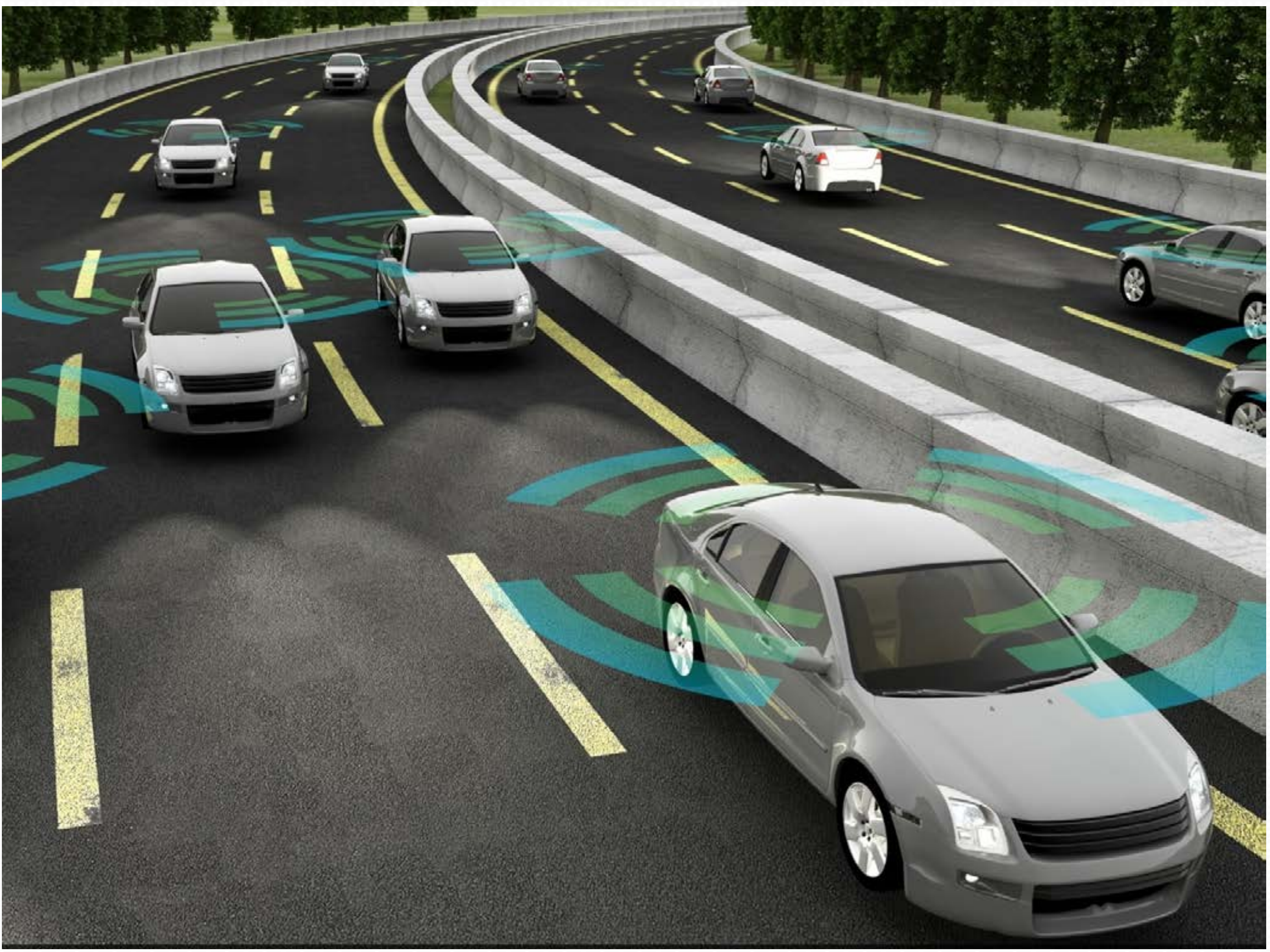
→

New Insights + Better Decision-Making

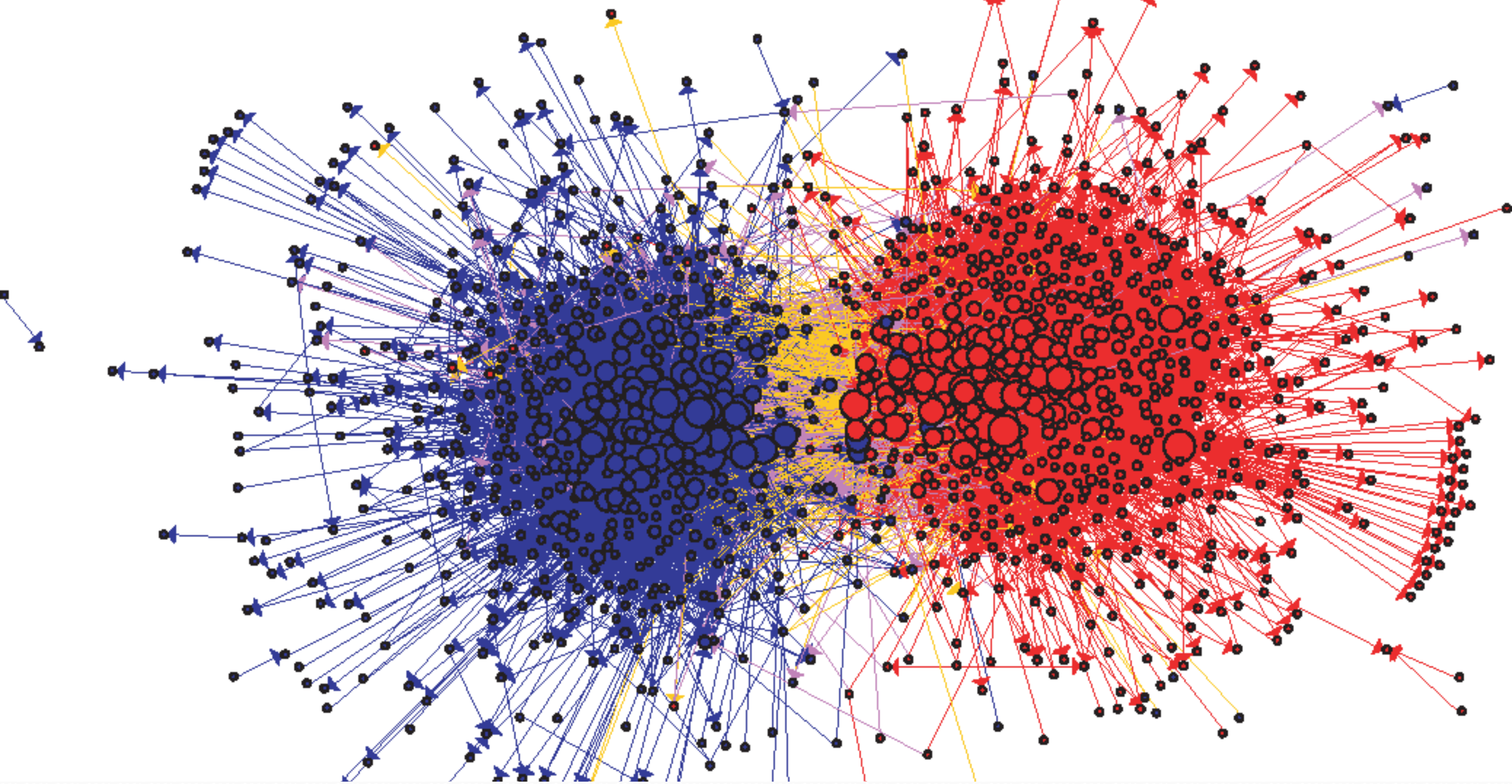
- Data to Insights to Action
- Resilience and Systemic Risk Management
- System Design and Architecture
- Social Welfare, Sustainability, and Policy Design

Our ability to understand data and develop actionable models across interconnected systems, is at the core of being able to uncover new insights and solutions.

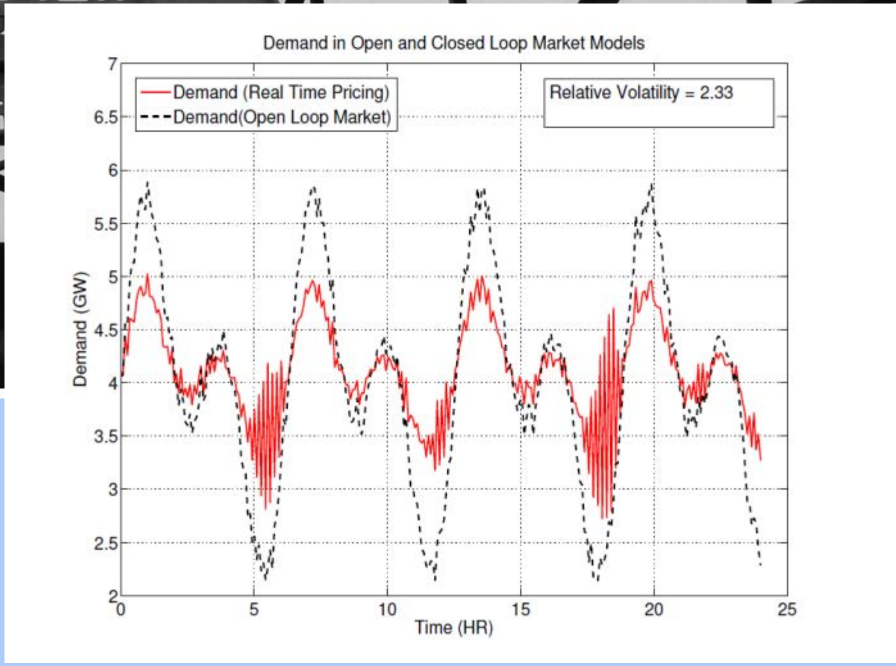
IDSS
MIT INSTITUTE FOR DATA, SYSTEMS, AND SOCIETY



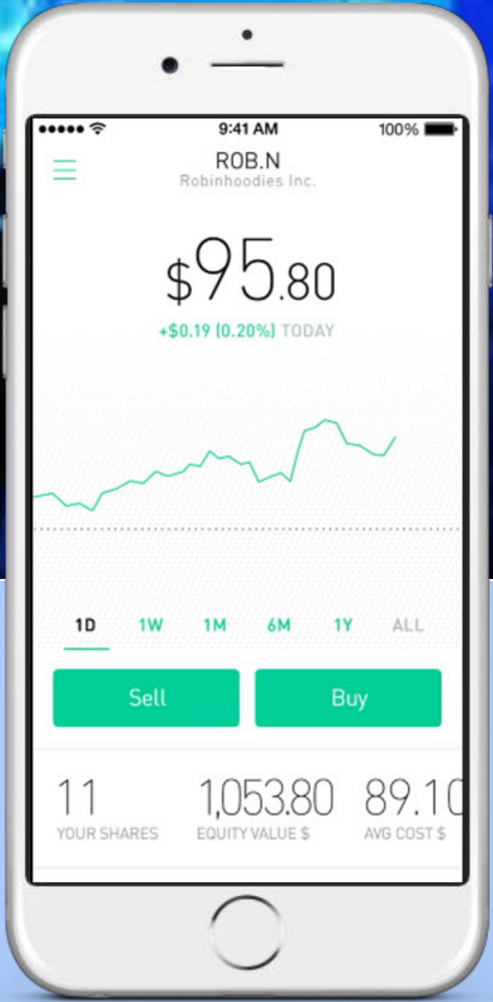
Connected, Self-Driving Cars Present New Solutions and Challenges



Social Media is Transforming the Way We Share --- and Consume -- Information



Power Systems and Pricing Increasingly Complex



How Do We Understand Systemic Risk in a Global, Interconnected Market?

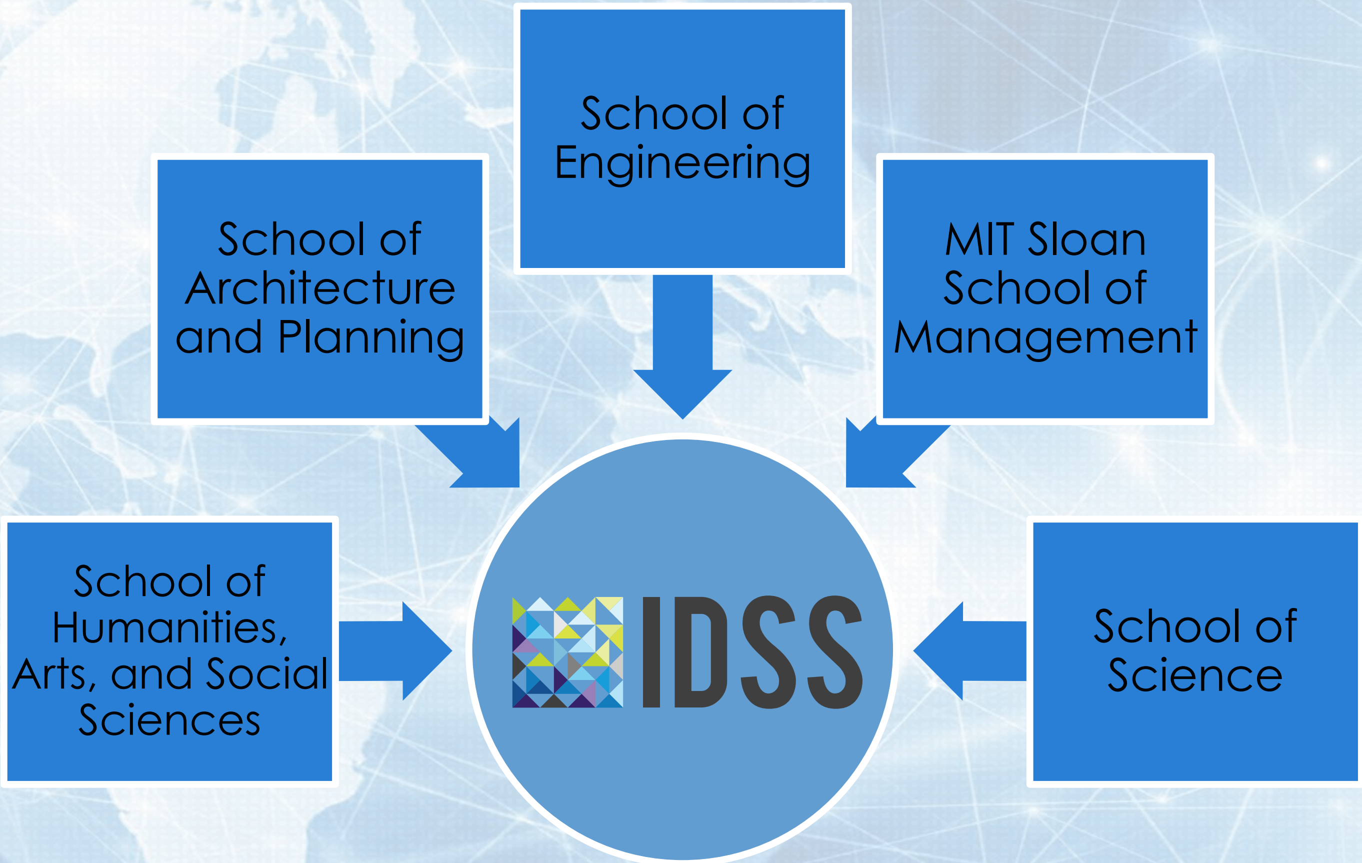
How Can We Predict Choices and Behavior to Develop Better Goods and Services?

MIT INSTITUTE FOR DATA, SYSTEMS, AND SOCIETY

IDSS

Teaching and Research

IDSS Has the Support and Involvement of All Five Schools of MIT



- **Founded in 2015**
- **Interdisciplinary research at the core of its mission**
- **Supported by more than 80 core and affiliate faculty from across MIT**

IDSS Advances Both Teaching and Research

Teaching

- PhD, Social and Engineering Systems (SES) (40 students and growing)
- PhD in Statistics (planned 2018)
- Masters in Technology Policy (~120 students)
- Statistics Minor for Undergraduates
- MicroMasters in Data Science (planned 2018)
- Professional Education Courses (Online)

Research

- IDSS SES PhD Program
- Laboratory in Information and Decision Systems (LIDS)
- Statistics and Data Science Center
- Sociotechnical Systems Research Center

Teaching: The PhD in Social and Engineering Systems is in its Second Year with a total of 20 students

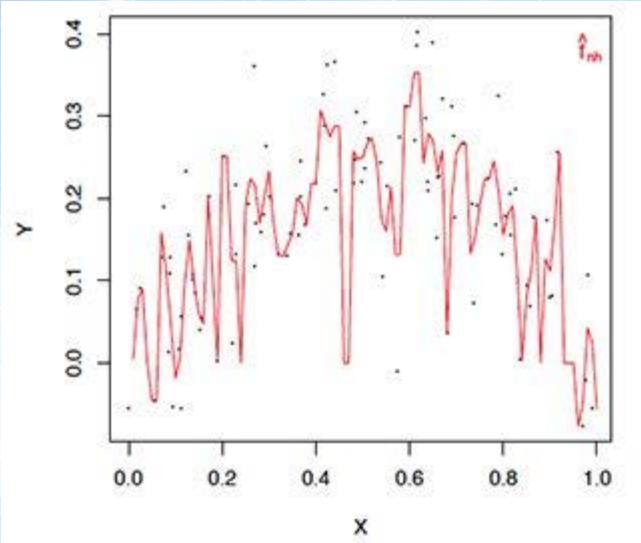
- SES PhD students study problems that correspond to significant societal challenges, in areas such as autonomous systems, energy systems, finance, social networks, and urban systems.
- Work includes analytical research that can be used to inform policy making.
- Graduates will go on to roles in academic departments in various fields, serve in the public sector (from research labs to regulatory agencies), as well as pursue careers in the private sector (from industry to consulting).

Teaching: The PhD in Statistics and Data Science to Launch in Fall, 2018

- The first Statistics and Data Science PhD at MIT, with an emphasis on 21st Century Statistics

- Interdisciplinary: aspiring students will apply through a “home department” such as Economics or Math.

- The program will offer students advanced training in statistics and data science, in combination with the strength and guidance of established departments at MIT.



Teaching: The Masters in Technology Policy is a 2-year Program, Comprising about 60 Students

- TPP addresses societal challenges through research and education at the intersection of technology and policy.
- Through our two-year Master of Science Program, we prepare students for leadership in government and industry.
- Degree requirements include graduate-level coursework in engineering, policy, economics and law, and an interdisciplinary thesis focused on a technology policy issue.

TPP

MIT Technology & Policy Program

Teaching: An Online Course Designed for Professional Learners

- Runs February 5, 2018 and May 7, 2018
- Featuring top faculty members at MIT
- Modules: Making Sense of Unstructured Data; Regression and Prediction; Classification, Hypothesis Testing and Anomaly Detection, Recommendation Systems, Networks and Graphical Models, Predictive Modeling,

An Online Data Science MicroMasters

John Tsitsiklis

Probability:
6.431x

Philippe Rigollet

Statistics:
18.6501x

Regina Barzilay &
Tommi Jaakkola

Machine Learning
6.86x

Esther Duflo
& Sara Ellison

Data Analysis
14.310x

- Four of MIT's highly courses, online
- Open to employees, students worldwide for free
  - Verified certificates available for a small fee (~$300/course)
- Classes start fall 2019

IDSS + edX MicroMasters™

An Online Data Science MicroMasters

- Recruitment Opportunities
  - Student Biographies
  - Student Resumes
  - Targeting by topic
- Employee Opportunities
  - Efficient investment in employee training
  - Boost retention, productivity
- Robust Verification of students
  - ID Verified Students
  - Proctored Exams
  - Anti-Cheating Algorithms

IDSS

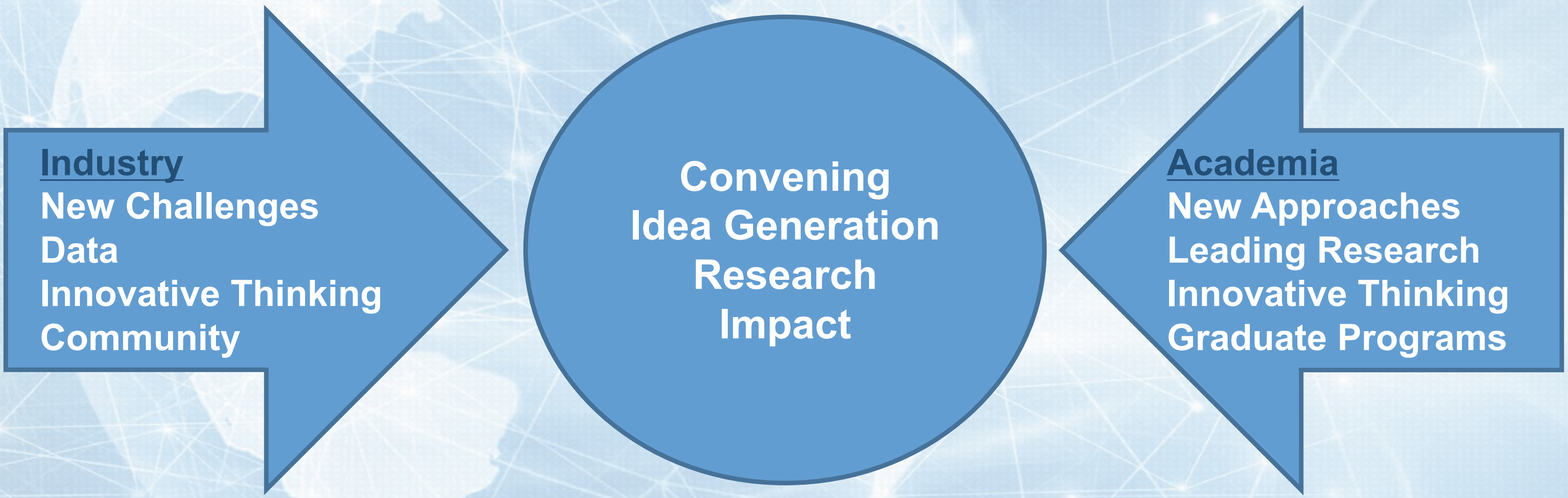
THOMSON REUTERS®

Booz | Allen | Hamilton

strategy and technology consultants

WORLDQUANT

Industry Partnerships Support Research, Collaboration and Impact



The Industry Partnership Program Offers a Relationship with IDSS Faculty and Students Across Areas of Interest to the Industry

- Meet with faculty and graduate students and identify opportunities to incorporate members' data assets into graduate student research projects
- Attend members-only workshops in the fall and the spring, for small group discussion with faculty, researchers and students
- Meet and interact with IDSS graduate students for the purpose of recruiting, both for internships and positions after graduation
- Join the IDSS External Advisory Board, which offers strategic advice and guidance to IDSS
- Attend conferences and workshops sponsored by IDSS and the Laboratory for Information and Decision Sciences (LIDS) as VIP guests
- Attend monthly seminars, hosted by IDSS, featuring MIT researchers, visiting faculty, and guests from industry and top universities