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13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Ali Jadbabaie-Moghadam
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	19b. TELEPHONE NUMBER 617-253-7339

RPPR Final Report

as of 08-Sep-2020

Agency Code:

Proposal Number: 61791CSMUR

Agreement Number: W911NF-12-1-0509

INVESTIGATOR(S):

Name: Ali Jadbabaie-Moghadam

Email: jadbabai@mit.edu

Phone Number: 6172537339

Principal: Y

Organization: **University of Pennsylvania**

Address: Office of Research Services, Philadelphia, PA 191046205

Country: USA

DUNS Number: 042250712

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Report Date: 06-Dec-2019

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Final Report for Period Beginning 01-Sep-2012 and Ending 06-Sep-2019

Title: Evolution of Cultural Norms and Dynamics of Socio-Political Change

Begin Performance Period: 01-Sep-2012

End Performance Period: 06-Sep-2019

Report Term: 0-Other

Submitted By: Ali Jadbabaie-Moghadam

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Phone: (617) 253-7339

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STEM Degrees:

STEM Participants:

Major Goals: Many of the central questions related to evolution of social and cultural norms and dynamics of sociopolitical change involve interactions among individuals and groups with different identities, influences and interactions. The understanding of these interactions is crucial for creating a new interdisciplinary science that on the one hand utilizes domain-specific expertise from economics, political economy, political science and sociology, and on the other hand leverages the advances in methodologies driven by the science of networks, systems theory, and computational social science, as well as our understanding of large scale networked systems. Throughout this MURI, Our goal has been to create new fundamental theories, analyses, experiments, methodologies, and predictive models that provide insight and understanding for the scientific community, policy makers, and the Army.

Contrary to common views of “universality” that is dominant in the network science literature, our focus on this project was to blend domain-specific knowledge social science theories with mathematics of networks and dynamic interactions.

Another major focus of this body of work has been on understanding how endogenous behavior relates to patterns of communication, dissemination of information, and expectations of others' behaviors. In summary, the goal of our research program is to address the following needs:

- Need for more quantitative approaches, beyond descriptive analysis
- Need for theory, principled modeling, data analysis, lab experiments, and field surveys
- Need to educate a new breed of computational social scientists and engineers.

The above project was kicked off in February 2013, and with an extension, it was completed in September of 2019.

Accomplishments: The project broke new grounds on multiple levels: First and foremost, it lead to the training of a diverse, and new generation of young scholars with a combined expertise in information sciences and computing as well as in social sciences.

The following is a partial list of students that were fully or partially supported on this grant and started a research career in Academia or industry:

MURI Postdocs and PHD students in a research career

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- Amir Ajorlou (Research Scientist), MIT
- Chinwendu Enyioha (Assistant Professor), University of Central Florida
- Ali Kakhbod (postdoc at MIT, then getting a second PhD in Economics from MIT)
- Arastoo Fazeli Neishabour (Data Scientist, YouTube)
- Rasul Tutunov (Senior Data Scientists, Hiawee Research, london)
- Mohammad Amin Rahimian, Assistant professor , university of Pittsburgh
- Hoda Heidari, Assistant Professor of Machine Learning, Carnegie Mellon University
- Vasileios Tzoumas, Assistant professor of Aerospace and Robotics, University of Michigan
- Pooya Molavi, Assistant profesor, Managerial Economcis, kellogg School of Business, Northwestern University (after 2 PhDs with jadbabaie and Acemoglu)
- Santiago Segarra, MIT IDSS postdoctotral fellow and then Assistant professor, Rice University
- Cesar Uribe, Assistant Professor, Rice University
- Isa Chaves - Assistant Professor, Northwestern Kellogg,
- Pietro Tebaldi - Assistant professor now at U of Chicago Economics,
- Yiqing Xing - Assistant professor Johns Hopkins Cary School of Business
- Stephen Nei - post doc, Nuffield College Oxford
- Kimon Drakopoulos, Assistant profeswsor, USC Marshall School of Business
- Austin Benson, postdoctoral fellow and then Assistant Professor of CS, Cornell University
- Leon Yao (PhgD student, Social and Engineering Systems, MIT
- Ali Makhdumi, Assistant Professor, Drecision Sciences, Fuqua Schoolk of Business, Duke University

The project also lead to new results on how patterns of communication, interaction, and learning in networked societies (Thrust 1) affect the evolution of behavior (Thrusts 2 and 3), how this understanding (the endogeneity of behavior) affects the optimal design of policies and interventions designed to influence beliefs and social norms (Thrust 4). In Thrust 3, we investigated the micro-foundations of local interaction models, and using domain-dependent knowledge, models, and data, we investigate how this leads us to understand evolution of social norms and social learning (Thrust 1), as well as social and political change, and role of development in both (Thrust 2), and finally how to control these phenomena using principled interventions (thrust 4). We coordinated the thrusts so that our modeling, analysis and theory work on models of local interaction which lead to dynamics of contagion, diffusion and cascade both inform our work on information aggregation and social learning as well as the thrust on political change.

The project expanded the new discipline of computational and quantitative social sciences and lead to creation of a new Institute at MIT called the Institute for Data, Systems, and Society (idss.mit.edu), and creation fo its flagship PhD program on Social and Engineering Systems

PI Jadbabaie moved to MIT to help start this new Institute with PIs Acemoglu, Ozdaglar, Dahleh, and Christia

Training Opportunities: The PIs held multiple workshops and conferences

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Results Dissemination: Ali Jadbabaie was the co-organizer of the inaugural Learning for Dynamics and Control Conference. This was held in May 2019 and was supported by NSF, ARO, ONR, and AFOSR and had 400 attendees

Ali Jadbabaie is a member of the Intelligence Science and Technology Experts Group (ISTEG) which advises Director of the Office of National Intelligence

Mathew Jackson wrote a book called "The Human Network"

<https://web.stanford.edu/~jacksonm/books.html#book2>

It discusses how a handful of simple and quantifiable features of human networks yield enormous insight into why we behave the way we do. Two threads are interwoven: why human networks have special features, and how those features determine our power, opinions, opportunities, behaviors, and accomplishments. Some of the topics included are: the different ways in which a person's position in a network determines their influence; which systematic errors we make when forming opinions based on what we learn from our friends; how financial contagions work and why are they different from the spread of a flu; how splits in our social networks feed inequality, immobility, and polarization; and how network patterns of trade and globalization are changing international conflict and wars.

The book is non-technical, with no equations but many pictures, and is full of rich examples and cases that illustrate the points. It is not only useful for explaining network science to a lay audience, but also as a supplement for a course on networks.

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Honors and Awards: MURI AWARDS (2013-2019)

Daron Acemoglu

- Nemmers Prize in Economics 2013
- Elected Member of the Turkish Academy of Sciences 2013
- Best Political Book of the Year Award for Why Nations Fail 2013
- Kadir Has Lifetime Contribution to Science Award, Kadir Has University 2013
- George S. Eccles Award for Excellence in Writing for Why Nations Fail 2013
- Turkish Presidential Culture and Arts Grand Award 2013
- Elected Member of the National Academy of Sciences 2014
- Honorary Doctorate, University of Athens 2014
- Honorary Doctorate, Bilkent University 2015
- Max Schmidheiny Award, St. Gallen Symposium 2015
- Honorary Doctorate, Bath University 2017
- Great Immigrant List of the Carnegie Foundation 2017
- BBVA Frontiers of Knowledge Award in Economics 2017
- Carnegie Fellow 2017
- Honorary Doctorate, ENS Paris-Saclay 2017
- Honorary Doctorate, London Business School 2018
- Jean-Jacques Laffont Prize, University of Toulouse 2018
- Global Economy Prize 2019
- MIT Institute Professor 2019

Mathew Jackson

President, Game Theory Society, 2020-2022, Executive Vice President, 2018-2020.
Game Theory Society Fellow, elected 2017.
John von Neumann Award, Rajk Laszlo College, 2015.
Member of the National Academy of Sciences, elected 2015.
Honorary Doctorate (Doctorat Honoris Causa), Aix-Marseille Universit'e, 2013.
Dean's Award for Distinguished Teaching in Humanities and Sciences, Stanford, 2013.

Jon Kleinberg

Harvey Prize (2013)
Allen Newell Award (2014)
Several Best Paper Awards(WWW, KDD, ...)
ACM Fellow

Asuman Ozdaglar

Spira Teaching Award 2014
Keithley Professorship in Electrical Engineering, MIT 2015
Middle East Technical University (METU, Turkey) Recognition Award 2018
Distinguished Professor of Engineering, MIT 2018
ICASSP B3st paper Award (2018)

Jure Leskovec

Microsoft Fellowship
Lagrange Prize

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Ali Jadbabaie

- Alfred Fittler Moore Professorship in Network Science, (2013)
- JR East Professorship, MIT (2016)
- ICASSP Best Paper Award (2018)
- Vannevar Bush Fellowship, Office of Undersecretary of Defense for Research and Engineering (2016)
- Winner, Best Student Paper Award,(as coauthor), IEEE Conference on Acoustics, Speech, and Signal Processing, ICASSP 2018
- Finalist, Student Best Paper Award, (as co-advisor), IEEE Conference on Decision and Control, Melbourne, Australia, December 2017
- Finalist, Student Best Paper Award, (as advisor), American Control Conference, June 2016
- Member, National Academies Intelligence Science and technology Experts group (IS-TEG), March 2017
- Finalist, Student Best Paper Award (as advisor), American Control Conference, 2016
- Class of 2014 IEEE Fellow, for contributions to the theory of multi-agent coordination and control

Munzer Dahleh

Fellow, International federation for Automatic Control (IFAC), 2018
George S Axelby Best Paper Prize, IEEE Control Systems Society, 2015,

Protocol Activity Status:

Technology Transfer: Ali Jadbabaie and postdoc Cesar Uribe collaborated with lanc e Kaplan at ARO

PARTICIPANTS:

Participant Type: PD/PI

Participant: Ali Jadbabaie

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Co PD/PI

Participant: Mathew O Jackson

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: Y

Other Collaborators:

Funding Support:

Participant Type: Co PD/PI

Participant: Daron Acemoglu

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: Y

Other Collaborators:

Funding Support:

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Participant Type: Co PD/PI
Participant: Asuman E Ozdaglar
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co PD/PI
Participant: Munther Dahleh
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co PD/PI
Participant: Jon Kleinberg
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: Y
Other Collaborators:

Funding Support:

Participant Type: Co PD/PI
Participant: Larry Blume
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co PD/PI
Participant: Michael Kearns
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Staff Scientist (doctoral level)
Participant: Amir Ajorlou
Person Months Worked: 12.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N

Funding Support:

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as of 08-Sep-2020

Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE Journal of Selected Topics in Signal Processing

Publication Identifier Type: DOI

Publication Identifier: 10.1109/JSTSP.2013.2246764

Volume: 7

Issue: 2

First Page #:

Date Submitted: 7/18/17 12:00AM

Date Published:

Publication Location:

Article Title: Reaching Consensus With Increasing Information

Authors: Pooya Molavi, Ali Jadbabaie, Kamiar Rahnema Rad, Alireza Tahbaz-Salehi

Keywords: Consensus, distributed detection, learning, social networks

Abstract: This paper focuses on a model of opinion formation over networks with continuously flowing new information and studies the relationship between the network and information structures and agents' ability to reach agreement. At each time period, agents receive private signals in addition to observing the beliefs held by their neighbors in a network. Each agent then updates its belief by aggregating the information available to it in a boundedly rational fashion. Whether this model results in conformity or disparity of beliefs is contingent on connectivity of the network and identifiability of the unknown state. We show that if the network is strongly connected, agents will eventually reach consensus in their beliefs; if in addition the state is globally identifiable, then agents will be able to learn the unknown state. Agents will also reach consensus and learn the state if the network fails to be connected but the state is locally identifiable. In contrast, agents in a non-strongly conn

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE Transactions on Control of Network Systems

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TCNS.2014.2310911

Volume: 1

Issue: 1

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Date Submitted: 9/7/16 12:00AM

Date Published:

Publication Location:

Article Title: Optimal Resource Allocation for Network Protection Against Spreading Processes

Authors: Victor M. Preciado, Michael Zargham, Chinwendu Enyioha, Ali Jadbabaie, George J. Pappas,

Keywords: network analysis and control, Biomedical systems, markov processes

Abstract: We study the problem of containing spreading processes in arbitrary directed networks by distributing protection resources throughout the nodes of the network. We consider that two types of protection resources are available: 1) preventive resources able to defend nodes against the spreading (such as vaccines in a viral infection process) and 2) corrective resources able to neutralize the spreading after it has reached a node (such as antidotes). We assume that both preventive and corrective resources have an associated cost and study the problem of finding the cost-optimal distribution of resources throughout the nodes of the network. We analyze these questions in the context of viral spreading processes in directed networks. We study the following two problems: 1) given a fixed budget, find the optimal allocation of preventive and corrective resources in the network to achieve the highest level of containment and 2) when a budget is not specified, find the minimum budget required to

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Journal: American Economic Review

Publication Identifier Type: DOI

Publication Identifier: 10.1257/aer.104.4.1350

Volume: 104

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Date Submitted: 9/7/16 12:00AM

Date Published:

Publication Location:

Article Title: Cycles of Conflict: An Economic Model

Authors: Daron Acemoglu, Alexander Wolitzky

Keywords: Bayesian, Economic Model

Abstract: We propose a model of cycles of conflict and distrust. Overlapping generations of agents from two groups sequentially play coordination games under incomplete information about whether the other side consists of bad types who always take bad actions. Good actions may be misperceived as bad and information about past actions is limited. Conflict spirals start as a result of misperceptions but also contain the seeds of their own dissolution: Bayesian agents eventually conclude that the spiral likely started by mistake, and is thus uninformative of the opposing group's type. The agents then experiment with a good action, restarting the cycle.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences

Publication Identifier Type: DOI

Publication Identifier: 10.1098/rsta.2012.0378

Volume: 371

Issue: 1987

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Date Submitted: 9/7/16 12:00AM

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Article Title: Analysis of large-scale social and information networks

Authors: Jon Kleinberg

Keywords: social networks Web systems graph theory

Abstract: The growth of the Web has required us to think about the design of information systems in which large-scale computational and social feedback effects are simultaneously at work. At the same time, the data generated by Web-scale systems—recording the ways in which millions of participants create content, link information, form groups and communicate with one another—have made it possible to evaluate long-standing theories of social interaction, and to formulate new theories based on what we observe. These developments have created a new level of interaction between computing and the social sciences, enriching the perspectives of both of these disciplines. We discuss some of the observations, theories and conclusions that have grown from the study of Web-scale social interaction, focusing on issues including the mechanisms by which people join groups, the ways in which different groups are linked together in social networks and the interplay of positive and negative interactions in these

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Journal: ACM Transactions on Economics and Computation

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Publication Identifier: 10.1145/2538508

Volume: 1

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Date Submitted: 9/7/16 12:00AM

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Publication Location:

Article Title: Binary Opinion Dynamics with Stubborn Agents

Authors: ERCAN YILDIZ, ASUMAN OZDAGLAR, DARON ACEMOGLU, AMIN SABERI, ANNA SCAGLIONE

Keywords: binary opinion dynamics, social networks, stubborn agents

Abstract: We study binary opinion dynamics in a social network with stubborn agents who influence others but do not change their opinions. We focus on a generalization of the classical voter model by introducing nodes (stubborn agents) that have a fixed state. We show that the presence of stubborn agents with opposing opinions precludes convergence to consensus; instead, opinions converge in distribution with disagreement and fluctuations. In addition to the first moment of this distribution typically studied in the literature, we study the behavior of the second moment in terms of network properties and the opinions and locations of stubborn agents. We also study the problem of optimal placement of stubborn agents where the location of a fixed number of stubborn agents is chosen to have the maximum impact on the long-run expected opinions of agents.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: IEEE Transactions on Cybernetics

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TSMCB.2012.2236553

Volume: 43

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Date Submitted: 9/7/16 12:00AM

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Article Title: Network Formation: Neighborhood Structures, Establishment Costs, and Distributed Learning

Authors: Georgios Chasparis, Jeff Shamma

Keywords: wireless networks, Ad hoc networks, distributed algorithms, distributed network formation, game theory, learning automata

Abstract: We consider the problem of network formation in a distributed fashion. Network formation is modeled as a strategic-form game, where agents represent nodes that form and sever unidirectional links with other nodes and derive utilities from these links. Furthermore, agents can form links only with a limited set of neighbors. Agents trade off the benefit from links, which is determined by a distance-dependent reward function, and the cost of maintaining links. When each agent acts independently, trying to maximize its own utility function, we can characterize "stable" networks through the notion of Nash equilibrium. In fact, the introduced reward and cost functions lead to Nash equilibria (networks), which exhibit several desirable properties such as connectivity, bounded-hop diameter, and efficiency (i.e., minimum number of links). Since Nash networks may not necessarily be efficient, we also explore the possibility of "shaping" the set of Nash networks through the introduction of state-

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Date Submitted: 9/7/16 12:00AM

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Publication Location:

Article Title: The Diffusion of Microfinance

Authors: ABHIJIT BANERJEE, ARUN G. CHANDRASEKHAR, ESTHER DUFLO, MATTHEW O. JACKSON

Keywords: Microfinance, Diffusion, Social Networks, Peer Effects

Abstract: We examine how participation in a microfinance program diffuses through social networks, using detailed demographic, social network, and participation data from 43 villages in South India. We exploit exogenous variation in the importance (in a network sense) of the people who were first informed about the program, the "injection points." Microfinance participation is significantly higher when the injection points have higher eigenvector centrality. We also estimate structural models of diffusion that allow us to (i) determine the relative roles of basic information transmission versus other forms of peer influence, and (ii) distinguish information passing by participants and nonparticipants. We find that participants are significantly more likely to pass information on to friends and acquaintances than informed non-participants. However, information passing by non-participants is still substantial and significant, accounting for roughly one-third of informedness and participation.

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Publication Identifier: 10.1073/pnas.1400826111

Volume: 111

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Publication Location:

Article Title: Culture-dependent strategies in coordination games

Authors: Matthew O. Jackson, Yiqing Xing

Keywords: homophily, convention, social networks, focal point, inequality

Abstract: We examine different populations' play in coordination games in online experiments with over 1,000 study participants. Study participants played a two-player coordination game that had multiple equilibria: two equilibria with highly asymmetric payoffs and another equilibrium with symmetric payoffs but a slightly lower total payoff. Study participants were predominantly from India and the United States. Study participants residing in India played the strategies leading to asymmetric payoffs significantly more frequently than study participants residing in the United States who showed a greater play of the strategy leading to the symmetric payoffs. In addition, when prompted to play asymmetrically, the population from India responded even more significantly than those from the United States. Overall, study participants' predictions of how others would play were more accurate when the other player was from their own populations, and they coordinated significantly more frequently and earned

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Volume: 1

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Date Submitted: 9/7/16 12:00AM

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Article Title: Network Formation in the Presence of Contagious Risk

Authors: LAWRENCE BLUME, DAVID EASLEY, JON KLEINBERG, ROBERT KLEINBERG, EVA TARDOS

Keywords: Networks, contagion, network formation, Economics, Theory

Abstract: There are a number of domains where agents must collectively form a network in the face of the following trade-off: each agent receives benefits from the direct links it forms to others, but these links expose it to the risk of being hit by a cascading failure that might spread over multistep paths. Financial contagion, epidemic disease, the exposure of covert organizations to discovery, and electrical power networks are all settings in which such issues have been articulated. Here we formulate the problem in terms of strategic network formation, and provide asymptotically tight bounds on the welfare of both optimal and stable networks. We find that socially optimal networks are, in a precise sense, situated just beyond a phase transition in the behavior of the cascading failures, and that stable graphs lie slightly further beyond this phase transition, at a point where most of the available welfare has been lost. Our analysis enables us to explore such issues as the trade-offs between

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Publication Identifier: 10.1257/aer.104.12.4184

Volume: 104

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Date Submitted: 9/7/16 12:00AM

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Publication Location:

Article Title: Present Bias and Collective Dynamic Choice in the Lab

Authors: Matthew O. Jackson, Leeat Yariv

Keywords: Rent-seeking, Lobbying, Elections, Voting Behavior, Social Choice

Abstract: We study collective decisions by time-discounting individuals choosing a common consumption stream. We show that with any heterogeneity in time preferences, utilitarian aggregation necessitates a present bias. In lab experiments three quarters of "social planners" exhibited present biases, and less than two percent were time consistent. Roughly a third of subjects acted as if they were pure utilitarians, and the rest chose as if they also had varying degrees of distributional concerns.

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Publication Identifier Type: DOI Publication Identifier: 10.1257/aer.104.10.3115
Volume: 104 Issue: 10 First Page #:
Date Submitted: 9/7/16 12:00AM Date Published:
Publication Location:

Article Title: Financial Networks and Contagion

Authors: Matthew Elliott, Benjamin Golub, Matthew O. Jackson

Keywords: Network Formation, Financing Policy, Bankruptcy, Liquidation

Abstract: We study cascades of failures in a network of interdependent financial organizations: how discontinuous changes in asset values (e.g., defaults and shutdowns) trigger further failures, and how this depends on network structure. Integration (greater dependence on counterparties) and diversification (more counterparties per organization) have different, nonmonotonic effects on the extent of cascades. Diversification connects the network initially, permitting cascades to travel; but as it increases further, organizations are better insured against one another's failures. Integration also faces trade-offs: increased dependence on other organizations versus less sensitivity to own investments. Finally, we illustrate the model with data on European debt cross-holdings.

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Publication Identifier Type: DOI Publication Identifier: 10.1257/jep.28.4.3
Volume: 28 Issue: 4 First Page #:
Date Submitted: 9/7/16 12:00AM Date Published:
Publication Location:

Article Title: Networks in the Understanding of Economic Behaviors

Authors: Matthew O. Jackson

Keywords: Consumer Economics, Learning, Information and Knowledge, Communication, Unawareness, Network Formation and Analysis, Theory, Economic Sociology; Economic Anthropology, Social and Economic Stratification

Abstract: As economists endeavor to build better models of human behavior, they cannot ignore that humans are fundamentally a social species with interaction patterns that shape their behaviors. People's opinions, which products they buy, whether they invest in education, become criminals, and so forth, are all influenced by friends and acquaintances. Ultimately, the full network of relationships—how dense it is, whether some groups are segregated, who sits in central positions—affects how information spreads and how people behave. Increased availability of data coupled with increased computing power allows us to analyze networks in economic settings in ways not previously possible. In this paper, I describe some of the ways in which networks are helping economists to model and understand behavior. I begin with an example that demonstrates the sorts of things that researchers can miss if they do not account for network patterns of interaction. Next I discuss a taxonomy of network properties and

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Volume: Issue:

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Date Submitted: 9/7/16 12:00AM

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Article Title: Dynamic Pricing in Social Networks: The Word of Mouth Effect

Authors: Amir Ajorlou, Ali Jadbabaie, Ali Kakhbod

Keywords: Information diffusion, word of mouth, price fluctuations, social networks, network externality, homophily, zero pricing, monopoly pricing

Abstract: We study the problem of optimal dynamic pricing for a monopolist selling a product to consumers in a social network. In the proposed model, the only means of spread of information about the product is via Word of Mouth communication; consumers' knowledge of the product is only through friends who already know about the product's existence. Both buyers and non-buyers contribute to information diffusion while buyers are more likely to get engaged. By analyzing the structure of the underlying endogenous process, we show that the optimal dynamic pricing policy for durable products with zero or negligible marginal cost, drops the price to zero infinitely often. By attracting low-valuation agents with free-offers and getting them more engaged in the spread, the firm can reach out to potential high-valuation consumers in parts of the network that would otherwise remain untouched without the price drops. We provide evidence for this behavior from smartphone app market, where price histories in

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Publication Identifier: 10.1016/j.jet.2014.11.002

Volume: 156 Issue:

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Article Title: Introduction to computer science and economic theory

Authors: Lawrence Blume, David Easley, Jon Kleinberg, Robert Kleinberg, Eva Tardosa

Keywords: Algorithmic game theory, Implementation, Learning in games, Mechanism design, Networks

Abstract: This essay introduces the symposium on computer science and economic theory.

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Journal: IEEE Transactions on Control of Network Systems

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Publication Identifier: 10.1109/TCNS.2015.2444031

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Article Title: Minimal Actuator Placement with Bounds on Control Effort

Authors: V. Tzoumas, M. A. Rahimian, G. J. Pappas, A. Jadbabaie

Keywords: Controllability energy metrics, input placement, leader selection, minimal network controllability, multiagent networked systems.

Abstract: We address the problem of minimal actuator placement in a linear system subject to an average control energy bound. First, following the recent work of Olshevsky, we prove that this is NP-hard. Then, we provide an efficient algorithm which, for a given range of problem parameters, approximates up to a multiplicative factor of $O(\log n)$, with n being the network size, any optimal actuator set that meets the same energy criteria; this is the best approximation factor one can achieve in polynomial time in the worst case. Moreover, the algorithm uses a perturbed version of the involved control energy metric, which we prove to be supermodular. Next, we focus on the related problem of cardinality-constrained actuator placement for minimum control effort, where the optimal actuator set is selected so that an average input energy metric is minimized. While this is also an NP-hard problem, we use our proposed algorithm to efficiently approximate its solutions as well. Finally, we run our algorithm

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Article Title: Robust Network Routing under Cascading Failures

Authors: Keban Savla, Giacomo Como, Munther A. Dahleh

Keywords: Failure analysis, Power system faults, Power system protection, Upper bound, Analytical models

Abstract: 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 is 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 either due to overload condition on itself or on all of its immediate downstream links. The coupling between link activation and flow dynamics implies that links to 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, an

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Publication Location:

Article Title: Information cartography

Authors: Dafna Shahaf, Carlos Guestrin, Eric Horvitz, Jure Leskovec

Keywords: datasets, multiple domains, complex information landscapes

Abstract: A metro map can tell a story, as well as provide good directions. key insights ?? Though human attention and comprehension can be overwhelmed by the data deluge, automatic methods can extract structured knowledge and provide maps of complex information landscapes to help people understand ideas, connections, and storylines. ?? Properties of good maps are difficult to formalize; important characteristics include coherence of storylines, coverage of diverse and important topics, and relationships among pieces of information. ?? These principles can be used to synthesize meaningful narratives from large datasets across multiple domains, including news stories, research papers, legal cases, and works of literature.

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Date Submitted: 9/7/16 12:00AM Date Published:
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Article Title: Competitive Diffusion in Social Networks: Quality or Seeding?

Authors: Arastoo Fazeli, Amir Ajorlou, Ali Jadbabaie

Keywords: social networks, strategic model

Abstract: Abstract—In this paper, we study a strategic model of marketing and product consumption in social networks. We consider two firms in a market competing to maximize the consumption of their products. Each firm has a limited budget which can be invested on the quality of the product or spent on seeding key individuals in the network to incentivize others to consume more of their product. After the decision of firms, agents choose their consumptions following a myopic best response dynamics which results in a local, linear update for their consumption decision. We characterize the unique Nash equilibrium of the game between firms and study the effect of the budgets as well as the network structure on the optimal allocation. We show that at the equilibrium, firms invest more budget on quality when their budgets are close to each other. However, as the gap between budgets widens, competition in qualities becomes less effective and firms spend more of their budget on seeding.

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Volume: 113 Issue: 4 First Page #: 913
Date Submitted: 9/7/16 12:00AM Date Published: 1/1/16 5:00AM
Publication Location:

Article Title: Private algorithms for the protected in social network search

Authors: Michael Kearns, Aaron Roth, Zhiwei Steven Wu, Grigory Yaroslavtsev

Keywords: data privacy, social networks, counterterrorism

Abstract: Motivated by tensions between data privacy for individual citizens and societal priorities such as counterterrorism and the containment of infectious disease, we introduce a computational model that distinguishes between parties for whom privacy is explicitly protected, and those for whom it is not (the targeted subpopulation). The goal is the development of algorithms that can effectively identify and take action upon members of the targeted subpopulation in a way that minimally compromises the privacy of the protected, while simultaneously limiting the expense of distinguishing members of the two groups via costly mechanisms such as surveillance, background checks, or medical testing. Within this framework, we provide provably privacy-preserving algorithms for targeted search in social networks. These algorithms are natural variants of common graph search methods, and ensure privacy for the protected by the careful injection of noise in the prioritization of potential targets. We val

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Date Submitted: 10/28/16 12:00AM **Date Published:** 10/24/16 3:41PM
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Article Title: Mapping Shiite Opinion: Insights from the Arba'een Pilgrimage

Authors: Fotini Christia, Elizabeth Dekeyser, Dean Knox

Keywords: Iraq, Shiites, Sunnis, Iran, Karbala, pilgrims, Attitudes, Survey

Abstract: In the weeks leading up to November 21, millions of Shiite Muslims will flock to the southern Iraqi city of Karbala for the world's largest annual pilgrimage. Although the Arba'een pilgrimage has recently swelled to about ten times the size of the Hajj, it remains virtually unknown in the West. Pilgrims from across the world perform this ziyara—or visit to the shrine of the Prophet Muhammad's grandson, Imam Hussein—on foot to mark 40 days after his martyrdom. The event commemorates a central moment in the Sunni-Shiite divide and was largely restricted during the rule of Saddam Hussein, who saw the massive physical mobilization of Shiites as an implicit threat to his regime. Since Saddam's fall, participation in such religious festivals has risen steeply. We used the unique opportunity afforded by last year's Arba'een pilgrimage, which attracted a reported 22 million pilgrims, to survey over 4,000 observant men and women from Iran and Iraq for the first time ever.

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ARO MURI: Evolution of Cultural Norms and Dynamics of Sociopolitical Change

Final Report

A. Jadbabaie¹, Michael Kearns (Penn)

D. Acemoglu, F. Christia, A. Ozdaglar, and M. Dahleh (MIT)

Larry Blume, Jon Kleinberg (Cornell)¹

Jure Leskovec, Matt Jackson (Stanford)

1. Background and Introduction

This document is the final progress report for the ARO MURI project on Evolution of Cultural Norms and Dynamics of Socio-political change. The project started in Fall 2012 with kick-off event occurring on February 2013. The project received an extension in 2018 and it concluded in Fall 2019. The project brought together a unique mix of world experts in computational science, network science, political science, economics, and decision making together.

Many of the central questions related to evolution of social and cultural norms and dynamics of sociopolitical change involve interactions among individuals and groups with different identities, influences and interactions. The understanding of these interactions is crucial for creating a new interdisciplinary science that on the one hand utilizes domain-specific expertise from economics, political economy, political science and sociology, and on the other hand leverages the advances in methodologies driven by the science of networks, systems theory, and computational social science, as well as our understanding of large scale networked systems. Throughout this MURI, Our goal has been to create new fundamental theories, analyses, experiments, methodologies, and predictive models that provide insight and understanding for the scientific community, policy makers, and the Army.

Contrary to common views of “universality” that is dominant in the network science literature, our focus on this project was to blend domain-specific knowledge social science theories with mathematics of networks and dynamic interactions.

Another major focus of this body of work has been on understanding how endogenous behavior relates to patterns of communication, dissemination of information, and expectations of others' behaviors. In summary, the goal of our research program is to address the following needs:

- Need for more quantitative approaches, beyond descriptive analysis
- Need for theory, principled modeling, data analysis, lab experiments, and field surveys
- Need to educate a new breed of computational social scientists and engineers.

The above project was kicked off in February 2013, and with an extension, it was completed in September of 2019.

¹ PI Ali Jadbabaie moved to MIT in July 2016

Graduated PhD students and postdocs of the MURI who Pursued a Research Career

Our project broke new grounds on multiple levels: First and foremost, it led to the training of a diverse, and new generation of young scholars with a combined expertise in information sciences and computing as well as in social sciences.

The following is a partial list of students that were fully or partially supported on this grant and started a research career in Academia or industry:

- Amir Ajarlou (Research Scientist), MIT
- Chinwendu Enyioha (Assistant Professor), University of Central Florida
- Ali Kakhbod (postdoc at MIT, then getting a second PhD in Economics from MIT)
- Arastoo Fazeli Neishabour (Data Scientist, YouTube)
- Rasul Tutunov (Senior Data Scientists, Huawei Research, London)
- Mohammad Amin Rahimian, Assistant professor, University of Pittsburgh
- Hoda Heidari, Assistant Professor of Machine Learning, Carnegie Mellon University
- Vasileios Tzoumas, Assistant professor of Aerospace and Robotics, University of Michigan
- Pooya Molavi, Assistant professor, Managerial Economics, Kellogg School of Business, Northwestern University (after 2 PhDs with Jadbabaie and Acemoglu)
- Santiago Segarra, MIT IDSS postdoctoral fellow and then Assistant professor, Rice University
- Cesar Uribe, Assistant Professor, Rice University
- Isa Chaves, Assistant Professor, Northwestern Kellogg,
- Pietro Tebaldi, Assistant professor now at U of Chicago Economics,
- Yiqing Xing, Assistant professor, Johns Hopkins Carey School of Business
- Stephen Nei, post doc, Nuffield College Oxford
- Kimon Drakopoulos, Assistant professor, USC Marshall School of Business
- Austin Benson, postdoctoral fellow and then Assistant Professor of CS, Cornell University
- Leon Yao, PhD student, Social and Engineering Systems, MIT
- Ali Makhdoumi, Assistant Professor, Decision Sciences, Fuqua School of Business, Duke University
- Johan Ugander, Assistant Professor, Stanford University
- Bruno Abrahao, Assistant professor, NYU
- Michael Friedman, postdoctoral Scholar, Hebrew University, Jerusalem
- Spyros Zoumpoulis, INSEAD, Paris

Project Thrusts and Tasks

The project was divided into 4 Thrusts and multiple synergistic tasks as follows:

Thrust 1. Social change, social aggregation, and evolution of social norms

[S1] Evolution of social norms

[S2] Aggregation of beliefs and social learning

[S3] The emergence of generalized trust and economic outcomes

Thrust 2. Political change and societal stability:

[P1] Emergence of democracies and challenges to law and order

[P2] Field experiments: role of post-conflict development

[P3] Empirical study of social interaction on political change

[P4] Behavioral experiments in political and societal influence

Thrust 3. Modeling and analysis of social interaction, cascades, and contagion

[M1] Modeling of social interaction:

[M2] Modeling and analysis of cascades in networks

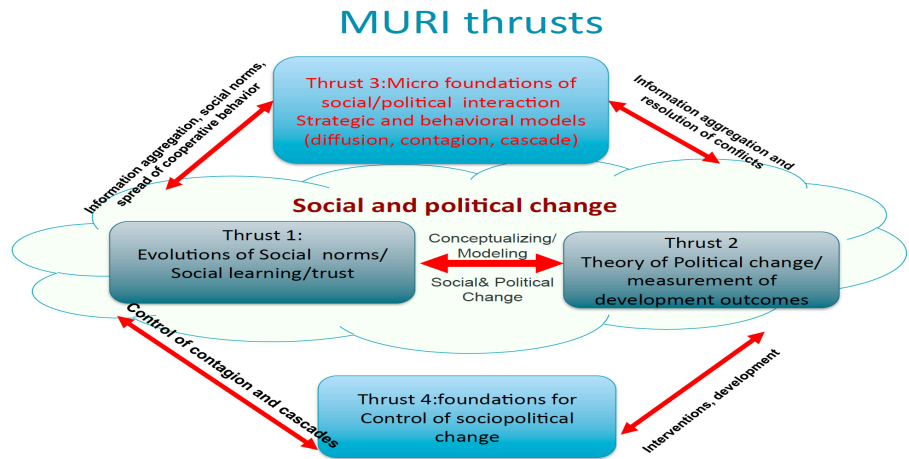
[M3] Idiosyncratic shocks, systemic risk

Thrust 4. Control of sociopolitical change

[C1] Static and Dynamic control of contagion processes

Synergies Between Thrusts

We investigated how patterns of communication, interaction, and learning in networked societies (Thrust 1) affect the evolution of behavior (Thrusts 2 and 3), how this understanding (the endogeneity of behavior) affects the optimal design of policies and interventions designed to influence beliefs and social norms (Thrust 4). In Thrust 3, we investigate the micro-foundations of local interaction models, and using domain-dependent knowledge, models, and data, we investigate how this leads us to understand evolution of social norms and social learning (Thrust 1), as well as social and political change, and role of development in both (Thrust 2), and finally how to control these phenomena using principled interventions (thrust 4). We have coordinated the thrusts so that our modeling, analysis and theory work on models of local interaction which lead to dynamics of contagion, diffusion and cascade both inform our work on information aggregation and social learning as well as the thrust on political change.



Team, Research Thrusts, and Connections

Thrusts and connections

Thrusts, Tasks and Milestones		
Network Science	Thrust 1. Social change, evolution of social norms	Jackson, Blume, Acemoglu, Jadbabaie
	[S1] Social change and evolution of social norms	
	[S2] Information aggregation and social learning	
	[S3] Emergence of generalized trust and economic outcomes	
Economics/Political Economy	Thrust 2. Political change and societal stability	Acemoglu, Christia, Leskovec, Jadbabaie, Dahleh, Kearns, Ozdaglar
	[P1] Emergence of democracies and challenges to law and order	
	[P2] Field experiments: role of post-conflict development	
	[P3] Empirical study of social interaction on political change	
Systems Theory	Thrust 3. Modeling and analysis of social interaction, cascades, and contagion	Kleinberg, Ozdaglar, Acemoglu, Leskovec, Dahleh, Jadbabaie, Kearns, Blume, Dahleh
	[M1] Modeling social interaction	
	[M2] Modeling and analysis of cascades in networks	
	[M3] Idiosyncratic shocks and cascades	
Computer Science	[M4] Robustness in multiagent simulation	Ozdaglar, Leskovec, Kleinberg, Jadbabaie, Dehleh
	Thrust 4. Control of Sociopolitical change	
	Control of contagion	
	Experiments/Field studies	

2. Technical Report

The project was culmination of the work of 10 PIs over a 7 year period, involving more than 25 students and postdoctoral researchers, with those who pursued a career research

and academia listed in the previous sections. Due to the topic of the project, these young scholars essentially laid the foundation of quantitative social sciences, by combining mathematics of networks, computing, and information sciences with social science disciplines ranging from sociology to Economics, Political Economy, and Political science

The project further led to many well-cited papers in *Proceedings of National Academy of Sciences*, *Science*, *Management Science*, *Operations Research*, *Econometrica*, *Journal of Political Economy*, *Review of Economic Studies*, *American Economic Review*, *Journal of Economic Theory*, *IEEE Transactions on Automatic Control*, *IEEE Transactions on Network Science and Engineering*, *IEEE Transactions on Signal Processing*, *IEEE Transactions on Information processing on Networks*, and many other top journals. Below each task, we have highlighted one project and then list the relevant publications. For each task, we provide a brief highlight of one project and then list all publications. Given the existence of Multiple Interim Reports, we mainly focus on the most important highlights here: The last section includes the list of awards and notable achievements of PIs. The code in bracket represents the task number. **S** stands for social norms (Thrust 1), **P** stands for political Change (Thrust 2). **M** stands for Thrust 3 (Modeling, identification and analysis of contagion). **C** stands for Control of sociopolitical change (thrust 4)

Most Important Highlights

[S1, S2, S3] Evolution of Social Norms, Social Learning

We have studied evolution of beliefs and social learning, and studies role of leadership coordination games of incomplete information. Jadbabaie and students have followed up their social learning work to create a behavioral foundation for non-Bayesian learning rules that were proposed in the literature. We consider a social and observational learning model, where a network of agents attempt to learn some unknown state of the world drawn by nature from a finite set. Agents observe private signals conditioned on the true state, and form beliefs about the unknown state accordingly. Each agent may face an identification problem in the sense that she cannot distinguish the truth in isolation. However, by communicating with each other, agents are able to benefit from side observations to learn the truth collectively.

In "[Foundations of Non-Bayesian Learning](#)," we present an axiomatic foundation for non-Bayesian learning rules that have been proposed in the literature over the past few years: we show exactly how these learning rules deviate from the Bayesian learning in networks, and what deviations from the Bayesian paradigm will still result in learning. In the revision, we show that in networks in which there are no multiple independent paths between any two nodes, the Bayesian paradigm satisfies all of our axioms except for the no-recall one. Furthermore, we delineate that for non-Bayesian updates, the degree of homogeneity of the social learning rule, as well as its curvature are important factors in whether learning, mislearning or non-learning occurs. We also show the effect of

changing weights, and show that learning is robust to changes in weights agents assign to each other beliefs, so long as weights do not decay too fast.

We note that the junior co-authors of this paper were students of PI Jadbabaie but both also worked with PI Acemoglu and are now Professors of Economics at Kellogg School at Northwestern University.

In "[Bayesian Learning without recall](#)," [2] we push one of these axioms further and analyze a model of learning and belief formation in networks in which agents follow Bayes rule yet they do not recall their history of past observations and cannot reason about how other agents' beliefs are formed. They do so by making rational inferences about their observations which include a sequence of independent and identically distributed private signals as well as the actions of their neighboring agents at each time. Successive applications of Bayes rule to the entire history of past observations lead to forebodingly complex inferences: due to lack of knowledge about the global network structure, and unavailability of private observations, as well as third party interactions preceding every decision. Such difficulties make Bayesian updating of beliefs an implausible mechanism for social learning. To address these complexities, we consider a Bayesian without Recall model of inference. On the one hand, this model provides a tractable framework for analyzing the behavior of rational agents in social networks. On the other hand, this model also provides a behavioral foundation for the variety of non-Bayesian update rules in the literature. We present the implications of various choices for the structure of the action space and utility functions for such agents and investigate the properties of learning, convergence, and consensus in special cases.

In [Bayesian Decision making in groups is Hard](#) [4] we study the computational aspects of fully rational decision making, and *for the first time* demonstrate that Bayesian computations in the network setting are computationally hard. While this was suspected, it was never shown formally. Many important real-world decision-making problems involve interactions of individuals with purely informational externalities, for example, in jury deliberations, expert committees, etc. We model such interactions of rational agents in a group, where they receive private information and act based on that information while also observing other people's beliefs or actions. As a Bayesian agent attempts to infer the truth from her sequence of observations of actions of others and her own private signal, she recursively refines her belief on the signals that other players could have observed and actions that they could have taken given that other players are also rational. The existing literature addresses asymptotic properties of Bayesian group decisions (important questions such as convergence to consensus and learning). In this work, we address the computations that the Bayesian agent should undertake to realize the optimal actions at every decision epoch. We use the iterated eliminations of infeasible signals (IEIS) to model the thinking process as well as the calculations of a Bayesian agent in a group decision scenario. We show that IEIS algorithm runs in exponential time; however, when the group structure is a partially ordered set the Bayesian calculations simplify and polynomial-time computation of the Bayesian recommendations is possible. We next shift attention to the case where agents reveal their beliefs (instead of actions) at every

decision epoch. We analyze the computational complexity of the Bayesian belief formation in groups and show that it is NP-hard. We also investigate the factors underlying this computational complexity and show how belief calculations simplify in special network structures or cases with strong inherent symmetries. We finally give insights about the statistical efficiency (optimality) of the beliefs and its relations to computational efficiency.

This work has been very influential and has resulted is accepted for publication in *Operations Research*.

In a separate paper that appeared in Conference on learning Theory, We further refine this result and show that [Reasoning in Bayesian Opinion Exchange Networks is Hard](#)

In [Local Optimality of Almost Piecewise-Linear Quantizers for Witsenhausen's Problem](#) [4], which just appeared [IEEE Transactions on Automatic Control](#) very recently, we address a problem that has been open since 1968: on optimal leadership strategies where the coordination between the leader and followers occurs across generations. In particular, we study a leader-follower coordination game in which the action of the leader is corrupted by an additive noise, before reaching the follower. The leader aims to coordinate with the follower while staying close to the observed state, recognizing that her action is not observed perfectly. As a result, she needs to signal the follower in a manner that can be decoded efficiently. This model is a reformulation of a well-known counterexample in team decision theory and game theory, for which the optimal strategy has been unknown since the inception of the model in 1960s. Very little is known about this model analytically, and our result is one of the first to shed some light

We pose Witsenhausen's problem as a leader-follower game of incomplete information. The follower makes a noisy observation of the leader's action (who moves first) and chooses an action minimizing her expected deviation from the leader's action. Knowing this, leader who observes the realization of the state, chooses an action that minimizes her distance to the state of the world and the ex-ante expected deviation from the follower's action. We study the perfect Bayesian equilibria of the game and identify a class of "near piecewise-linear equilibria" when leader cares much more about being close to the follower than the state, and the precision of the prior is poor. As a major consequence of this result, we prove the existence of a set of local minima for Witsenhausen's problem in form of slopy quantizers, which are at most a constant factor away from the optimal cost. We provide supporting theory for numerical investigations in the literature suggesting optimality of almost piecewise-linear strategies.

In [Social Norms and the Enforcement of Laws](#) we examine the interplay between social norms and the enforcement of laws. Agents choose a behavior (e.g., tax evasion, production of low-quality products, corruption, harassing behavior, substance abuse, etc.)

and then are randomly matched with another agent. There are complementarities in behaviors so that an agent's payoff decreases with the mismatch between her behavior and her partner's, and with overall negative externalities created by the behavior of others. A law is an upper bound (cap) on behavior. A law-breaker, when detected, pays a fine and has her behavior forced down to the level of the law. Equilibrium law-breaking depends on social norms because detection relies, at least in part, on whistle-blowing. Law-abiding agents have an incentive to whistle-blow on a law-breaking partner because this reduces the mismatch with their partners' behaviors as well as the negative externalities. When laws are in conflict with norms and many agents are breaking the law, each agent anticipates little whistle-blowing and is more likely to also break the law. Tighter laws (banning more behaviors), greater fines, and better public enforcement, all have counteracting effects, reducing behavior among law-abiding individuals but increasing it among law-breakers. We show that laws that are in strong conflict with prevailing social norms may backfire, whereas gradual tightening of laws can be more effective in influencing social norms and behavior.

Another related, complete paper is my joint work with Tarek Hassan and Ahmed Tahoun, [*The Power of the Street: Evidence from Egypt's Arab Spring*](#). During Egypt's Arab Spring, unprecedented popular mobilization and protests brought down Hosni Mubarak's government and ushered in an era of competition between three groups: elites associated with Mubarak's National Democratic Party (NDP), the military, and the Islamist Muslim Brotherhood. Street protests continued to play an important role during this power struggle. We use this series of events to investigate the role of popular mobilization on rent-seeking, corruption and weak institutions. We show that these protests are associated with differential stock market returns for firms connected to the three groups. Using daily variation in the number of protesters, we document that more intense protests in Tahrir Square are associated with lower stock market valuations for firms connected to the group currently in power relative to non-connected firms, but have no impact on the relative valuations of firms connected to other powerful groups. We further show that activity on social media may have played an important role in mobilizing protesters, but had no direct effect on relative valuations. According to our preferred interpretation, these events provide evidence that, under weak institutions, popular mobilization and protests have a role in restricting the ability of connected firms to capture excess rents. This paper just appeared in the [*Review of Financial Studies*](#).

Also, in [*Dynamic Public Learning in Networks of Strategic Agents: The Role of Inter/Intra-community Ties*](#), MURI Research scientists Amir Ajorlou, together with Ali Jadbabaie and Munther Dahleh study the quality of information aggregation in dynamic quadratic games of incomplete information. This model is influenced by earlier work of Jadbabaie's former student Alireza Tahbaz-Salehi, together with PIs Acemoglu and Ozdaglar. Agents in each generation have access to a public history of noisy aggregate actions in previous generations. Each agent also belongs to an information community, where they share a private noisy signal about the state. We quantify the quality of information aggregation as the asymptotic precision of the publicly learned signal about the state, and study how the interactions between/within information

communities affect the quality of learning. By characterizing the precision of aggregate learning for slow walks, we show the inefficiency of learning from the public history: while for a static state, public history fully reveals the state, a small perturbation in the state from generation to generation, significantly degrades the quality of public learning. As for the effect of information-action structure, we show that the inter-community interactions exhibit a double-edged effect: while the inter-community interaction of local influencers and influencees improves the quality of learning for slow dynamics, the inter-community interaction of global influencers and influencees defects learning for fast dynamics. As a result, we may observe phase transition in quality of learning between different information-action structures.

[1] "[Foundations of Non-Bayesian learning in networks](#)", P. Molavi, A. Tahbaz-Salehi, and A. Jadbabaie. *Econometrica*, March 2018

[3] "[Bayesian Learning without recall](#)", *IEEE Transactions on Signal and Information Processing over Networks*, Vol. 3, No. 3, Sep. 2017

[4] A. Ajorlou, A. Jadbabaie, "[Local Optimality of Almost Piecewise-Linear Quantizers for Witsenhausen's Problem](#)" [arXiv:1604.03806v5](#), 2019

[5] A. Rahimian, J Hazla, E. Mossel, and A. Jadbabaie, "Bayesian Learning in groups is Hard", *Operations Research*, to appear

[6] D. Acemoglu and M.O. Jackson, "[Social Norms and Enforcement of Laws](#)", *Journal of the European Economic Association*, Volume 15, Issue 2, 1 April 2017, Pages 245–295, <https://doi.org/10.1093/jeea/jvw006>

[7] Daron Acemoglu, Tarek A. Hassan, Ahmed Tahoun, "The Power of the Street: Evidence from Egypt's Arab Spring," *The Review of Financial Studies*, published online 26 Aug 2017, <https://doi.org/10.1093/rfs/hhx086>

[8] A. Ajorlou M. Dahleh, A. Jadbabaie, "Dynamic Public Learning in Networks of Strategic Agents: The Role of Inter/Intra-community Ties," *Proceedings of the IEEE Conference on Decision and Control*, Melbourne, Australia, December 2017.

[M1-M3] Modeling, identification, and analysis of social Interaction and Cascades

Our team has made significant progress in this area by following up on last year's work studying various aspects of local interaction models that focus on how one can solve an *inverse problem* related to contagion and determine how should one *seed* the network to get the desired contagion result.

In a new paper, "[Privacy-Constrained Network Formation](#)" [2] jointly written with Ali Makhdoumi, Azarakhsh Malekian and Asu Ozdaglar, and Daron Acemoglu, offers a new game of social network formation. With the increasing ease with which information can

be shared in social media, the issue of privacy has become central for the functioning of various online platforms. In this paper, we consider how privacy concerns affect individual choices in the context of a network formation game (where links can be interpreted as friendships in a social network, connections over a social media platform or trading activity in online platform). In the model, each individual decides which other agents to "befriend", i.e., form links with. Such links bring direct (heterogeneous) benefits from friendship and also lead to the sharing of information. But such information can travel over other linkages (e.g., shared by the party acquiring the information with others) through a percolation process over the equilibrium network. Privacy concerns are modeled as a disutility that individual suffers as a result of her private information being acquired by others, and imply that the individual has to take into account who the friends of her new friend (and who the friends of friends of her new friend etc.) are. We specify conditions under which pure-strategy equilibria exist and characterize both pure-strategy and mixed-strategy equilibria. Our two main results show that, as in many real-life examples, the resulting equilibrium networks feature clustered connections and homophily. Clustering emerges because if player a is friend with b and b is friend with c, then a's information is likely to be shared indirectly with c anyway, thus making it less costly for a to befriend c. Homophily emerges because even an infinitesimal advantage in terms of direct benefits of friendship within a group makes linkages within that group more likely, and the travel of information within that group reduces the costs, and thus increases the likelihood, of further within-group links. This paper is now published in the *Games and Economic Behavior*.

Kleinberg, together with Rahmtin Rotabi and Cristian Danescu-Niculescu-Mizil [2], investigated the spread of conventions through large social networks, using a source of data in which it was possible to trace these conventions and their evolution in fine-grained detail.

Crucial to this analysis is the idea of competition between conventions. In many domains, a latent competition among different conventions determines which one will come to dominate. One sees such effects in the success of community jargon, of competing frames in political rhetoric, or of terminology in technical contexts. These effects have become widespread in the on-line domain, where the ease of information transmission makes them particularly forceful, and where the available data offers the potential to study competition among conventions at a fine-grained level.

In analyzing the dynamics of conventions over time, however, even with detailed on-line data, one encounters two significant challenges. First, as conventions evolve, the underlying substance of their meaning tends to change as well; and such substantive changes confound investigations of social effects. Second, the selection of a convention takes place through the complex interactions of individuals within a community, and contention between the users of competing conventions plays a key role in the convention's evolution. Any analysis of the overall dynamics must take place in the presence of these two issues.

Rotabi, Danescu-Niculescu-Mizil, and Kleinberg[3] study a setting in which one can cleanly track the competition among conventions while explicitly taking these sources of complexity into account. The analysis is based on the spread of low-level authoring conventions in the e-print arXiv over 24 years and roughly a million posted papers: by tracking the spread of macros and other author-defined conventions, it is possible to study conventions that vary even as the underlying meaning remains constant. The finding is that the interaction among co-authors over time plays a crucial role in the selection of conventions; the distinction between more and less experienced members of the community, and the distinction between conventions with visible versus invisible effects, are both central to the underlying processes. This analysis enables predictions at the population level about the ultimate success of different synonymous conventions over time --- and at the individual level about the outcome of ``fights" between people over convention choices.

Furthermore, in a paper appearing in *Proceedings of the National Academy of Sciences* Kleinberg, together with Isabel Kloumann and Johan Ugander [4], provided theoretical guarantees for identifying community structures in large networks. Their particular focus was on what is known as the ``seed set expansion problem": given a subset of nodes from a community of interest in an underlying graph, can we reliably identify the rest of the community? The most widely used techniques for this problem, personalized PageRank and heat kernel methods, operate in the space of ``landing probabilities" of a random walk rooted at the seed set, ranking nodes according to weighted sums of landing probabilities of different length walks. Both schemes, however, lack an a priori relationship to the seed set objective.

The work of Kloumann, Ugander, and Kleinberg develops a principled framework for evaluating ranking methods by studying seed set expansion applied to the stochastic block model. It derives the optimal separator for the landing probabilities of two classes in a stochastic block model, and finds, surprisingly, that under reasonable assumptions the separator is asymptotically equivalent to personalized PageRank for a specific choice of the PageRank parameter (as a function of the block model parameters). This connection provides a novel formal motivation for the success of personalized PageRank in seed set expansion and node ranking generally. This connection can then be used to propose more advanced techniques incorporating higher moments of landing probabilities; these more advanced methods exhibit greatly improved performance despite being simple linear classification rules, and are even competitive with belief propagation.

[1] Daron Acemoglu, Ali Makhdoumi, Azaraksh Malekian, Asuman Ozdaglar, "[Privacy-constrained network formation](#)," *Games and Economic Behavior*, September 2017, Vol. 105, pp. 255-275. DOI: [10.1016/j.geb.2017.08.001](https://doi.org/10.1016/j.geb.2017.08.001)

[2] R. Rotabi, C. Danescu-Niculescu-Mizil, J. Kleinberg. [Tracing the Use of Practices through Networks of Collaboration](#). *Proceedings of 11th International AAI Conference*

on Weblogs and Social Media (ICWSM), 2017.

[3]R. Rotabi, C. Danescu-Niculescu-Mizil, J. Kleinberg. [Competition and Selection Among Conventions](#). *Proc. 11th International AAAI Conference on Weblogs and Social Media (ICWSM)*, 2017.

[4] I. Kloumann, J. Ugander, J. Kleinberg. [Block Models and Personalized PageRank](#). *Proceedings of the National Academy of Sciences*, 114(1) 33-38, 3 January 2017.
doi: 10.1073/pnas.1611275114

Social cascades (Jure Leskovec)

As information and behavior spreads from person to person in social networks, cascades can develop. However, as these cascades grow through complex macro- and micro-level processes, their future behavior is difficult to predict.

In our research we introduce methods for studying the mechanisms of such social cascades and for predicting their spread. Specifically, we present a framework for predicting a cascade's future trajectory, and develop methods that combine data mining and crowdsourcing techniques to explain how behavior spreads from individual to individual.

We aim to understand how individuals may influence adjacent others in a social network through their actions. In particular, our research focuses on the mechanisms that lead to negative behavior spreading in online communities.

We study how behavior cascades by looking at how antisocial behavior such as trolling may spread from person to person. While past literature has characterized such behavior as confined to a vocal, antisocial minority, we instead demonstrate that ordinary people, under the right circumstances, can become trolls, and that such behavior can percolate and escalate through a community.

While the social web has brought us closer together, it has also become a conduit for harassing others, for example, in the form of trolling. Negative behavior comprises a substantial fraction of user activity on many web sites. In fact, 40% of Internet users have experienced harassment in one form or another, while 73% have seen others harassed. Anecdotally, many of us can easily recall instances of others behaving badly in online settings – but what has led to this prevalence of negative behavior online?

While past literature has suggested that negative behavior is perpetuated by a small yet vocal antisocial minority, this chapter will demonstrate how ordinary individuals can act like trolls as well under the right circumstances. Combining data analysis of a large discussion community (CNN.com) with a controlled online laboratory experiment, we establish the causal factors that lead to people behaving

To manage bad content, many social sites have turned to voting as a way to curate the content that is showed to users. But despite these well-meaning intentions, voting, and in

particular, down-voting, can instead cause negative behavior to percolate. Not only are authors of down-voted content more likely to write content of worse quality in the future, but they are also more likely to be perceived worse by the community at large. Altogether, this research explores a future where systems can better mediate information sharing and interpersonal interaction, and thus promote the development of prosocial communities.

- [1] [Loyalty in Online Communities](#). W. Hamilton, J. Zhang, C. Danescu-Niculescu-Mizil, D. Jurafsky, J. Leskovec. *AAAI International Conference on Weblogs and Social Media (ICWSM)*, 2017.
- [2] [Community Identity and User Engagement in a Multi-Community Landscape](#). J. Zhang, W. Hamilton, C. Danescu-Niculescu-Mizil, D. Jurafsky, J. Leskovec. *AAAI International Conference on Weblogs and Social Media (ICWSM)*, 2017.
- [3] [Anyone Can Become a Troll: Causes of Trolling Behavior in Online Discussions](#). J. Cheng, M. Bernstein, C. Danescu-Niculescu-Mizil, J. Leskovec. *Computer-Supported Cooperative Work and Social Computing (CSCW)*, 2017. Best paper award.
- [4] [An Army of Me: Sockpuppets in Online Discussion Communities](#). S. Kumar, J. Cheng, J. Leskovec, V.S. Subrahmanian. *ACM International Conference on World Wide Web (WWW)*, 2017. Best paper award honorable mention.
- [5] [How Gamification Affects Physical Activity: Large-scale Analysis of Walking Challenges in a Mobile Application](#). A. Shamel, T. Althoff, A. Saberi, J. Leskovec. *ACM International Conference on World Wide Web (WWW)*, 2017.
- [6] [Online Actions with Offline Impact: How Online Social Networks Influence Online and Offline User Behavior](#). T. Althoff, J. Leskovec. *ACM International Conference on Web Search and Data Mining (WSDM)*, 2017.
- [7] [Why We Read Wikipedia](#). P. Singr, F. Lemmerich, R. West, L. Zia, E. Wulczyn, M. Strohmaier, J. Leskovec. *ACM International Conference on World Wide Web (WWW)*, 2017.
- [8] [Motifs in Temporal Networks](#). A. Paranjape, A. Benson, J. Leskovec. *ACM International Conference on Web Search and Data Mining (WSDM)*, 2017.

Fairness in machine Learning

Since 2015, coPI Kearns together with 2 MURI supported students (Jabbari and Heidari) have started a new research program focused on fairness in machine learning.

The widespread use of machine learning to make consequential decisions about individual citizens (such as those involving credit, employment, insurance, and education) has been accompanied by rising alarm over instances of bias or discrimination in the algorithms and models used. While legal, regulatory and watchdog challenges to discriminatory algorithms will play an important role, it is also crucial to examine and quantify the extent to which social norms such as fairness can be “endogenized” into the learning process itself. Can we develop a rigorous and useful science of fair machine learning? The early answer appears to be positive, although we also know it will not be simple, and that there will not be a single “right” definition of fairness for learning. Much

research to date has also focused on making the final output of a learning algorithm fair -- for instance, by ensuring that a learned classifier has approximately equal false positive or false negative rates across two subpopulations. Less attention has been paid to making the algorithms themselves fair, including during the training process. In recent work, we have made an effort in defining and designing fair learning algorithms for sequential decision-making, reinforcement learning, cross-population ranking, and other problems. Of particular interest is the effort to quantify the informational, computational and other costs of fairness compared to the classical non-fair settings.

In [Fairness in Reinforcement Learning](#) [1], Jabbari, Kearns and coauthors initiate the study of fairness in reinforcement learning, where the actions of a learning algorithm may affect its environment and future rewards. Our fairness constraint requires that an algorithm never prefers one action over another if the long-term (discounted) reward of choosing the latter action is higher. Our first result is negative: despite the fact that fairness is consistent with the optimal policy, any learning algorithm satisfying fairness must take time exponential in the number of states to achieve non-trivial approximation to the optimal policy. We then provide a provably fair polynomial time algorithm under an approximate notion of fairness, thus establishing an exponential gap between exact and approximate fairness.

In [A Convex Framework for Fair Regression](#) We introduce a flexible family of fairness regularizers for (linear and logistic) regression problems. These regularizers all enjoy convexity, permitting fast optimization, and they span the range from notions of group fairness to strong individual fairness. By varying the weight on the fairness regularizer, we can compute the efficient frontier of the accuracy-fairness trade-off on any given dataset, and we measure the severity of this trade-off via a numerical quantity we call the Price of Fairness (PoF). The centerpiece of our results is an extensive comparative study of the PoF across six different datasets in which fairness is a primary consideration.

[1] Shahin Jabbari, Matthew Joseph, Michael Kearns, Jamie Morgenstern, Aaron Roth ; [Fairness in Reinforcement Learning](#), *Proceedings of the 34th International Conference on Machine Learning*, PMLR 70:1617-1626, 2017.

[2] Richard Berk, Hoda Heidari, Shahin Jabbari, Matthew Joseph, Michael Kearns, Jamie Morgenstern, Seth Neel, Aaron Roth, [A Convex Framework for Fair Regression](#), [arXiv:1706.02409v1](#)

Furthermore, in [Mathematical foundations for social computing](#), Michael Kearns, provides an overview of social computing Communication of the ACM. Together with coauthors, he presents Social computing, which encompasses the mechanisms through which people interact with computational systems: crowdsourcing systems, ranking and recommendation systems, online prediction markets, citizen science projects, and collaboratively edited wikis, to name a few. These systems share the common feature that humans are active participants, making choices

that determine the input to, and therefore the output of, the system. The output of these systems can be viewed as a joint computation between machine and human, and can be richer than what either could produce alone. The term social computing is often used as a synonym for several related areas, such as “human computation” and subsets of “collective intelligence;” we use it in its broadest sense to encompass all of these things.

Jackson, together with Banerjee, Chandrasekhar, and Dufflo, are studying how the introduction of microfinance affects the networks of interactions among Indian villagers. Our data is from a two-wave panel from 2006 and 2012 covering network relationships between 16476 households in 75 Villages. Of those villages, none were exposed to microfinance in wave one, and 43 villages were by wave two. They compare network evaluation in village with and without microfinance entry. They find that networks exposed to microfinance become less dense, with links and triangles dissolving more rapidly (for credit relationship as well as other types of relationship). Using demographic and network data, They then classify households as having a high (H) or low (L) likelihood of participating in microfinance (when offered). They show that microfinance not only changes relationships among those likely to get loans (the H), but also relationships between those unlikely to get loans. These patterns are not consistent with standard models of network formation and link evolution. Those models either predict that LL links weakly increase, or decline but at most less than HL links. They show that new models of network formation, involving the formation of links and triangles and undirected search can match the results.

Jackson, together with Barbera studies how a revolt or protest succeeds only if sufficient people participate. They study how potential participants' ability to coordinate is affected by their information. They distinguish four phenomena that affect whether information either encourages or inhibits protests and revolutions:

- (i) Unraveling: When agents learn about each others' types, some are discouraged by meeting partisans of the status quo. This can unravel, as even confident agents realize that enough supporters will be discouraged to preclude a successful revolution.
- (ii) Homophily: Learning someone else's type under homophily is less informative since that individual is more likely to be similar to the learner. This can lead people to be less confident of a revolution, but can also stop potential unraveling.
- (iii) Extremism: Meeting other protestors, and seeing pilot demonstrations or outcomes in similar countries, reveal not only how much support for change exists, but also from which constituencies it emerges. This can undercut a revolution if factions differ sufficiently in their preferred changes.
- (iv) Counter Demonstrations: partisans for the status quo can hold counter-demonstrations to signal their strength.

They also discuss why holding mass demonstrations before a revolution may provide better signals of people's willingness to actively participate than other less costly forms

of communication (e.g., via social media), and how governments use redistribution and propaganda to avoid a revolution.

Jackson examined the "friendship paradox" (Feld 1991), which refers to the fact that, on average, people have strictly fewer friends than their friends have. He showed that this over-sampling of the most popular people amplifies behaviors that involve complementarities. People with more friends experience greater complementarities and hence take more extreme actions. Given the friendship paradox, people then perceive more extreme behavior when sampling their friends than exists in the overall population. Given the complementarities, this feeds back to amplify average behavior. In addition, people with the greatest innate proclivity to take high actions also tend to be the ones who choose to interact the most, leading to further feedback and amplification. These results are consistent with studies finding that people consistently overestimate peer consumption of alcohol, cigarettes, and drugs; and, can help explain problems with adolescent abuse of drugs and binge-drinking, as well as other behaviors. Jackson also discussed how these results change in cases of strategic substitutes, where individuals overestimate free-riding by peers.

Banerjee, Chandrasekhar, Duflo and Jackson continued their work studying network models of behavior and diffusion in rural Indian villages. They examined whether it possible to identify individuals who are highly central in a community without gathering any network information, simply by asking a few people, and whether people's nominees are successful when used as seeds for a diffusion process. They explore these questions theoretically, via surveys, and via field experiments, and show via a model of information flow how members of a community can, just by tracking gossip about others, identify highly central individuals in their network. Asking villagers in rural Indian villages to name good seeds for diffusion, they find that they accurately nominate those who are central according to a measure tailored for diffusion - not just those with many friends or in powerful positions. Finally, they run a randomized field experiment in 213 other villages that tests how effective it is to use such nominations as seeds for a diffusion process. Relative to random seeds or those with high social status, hitting at least one seed nominated by villagers leads to more than a 65% increase in the spread of information.

Chandrasekhar and Jackson further advanced their study of a new class of random-graph models, 'subgraph generation models', for the statistical estimation of network formation that allow for substantial correlation in links. They developed a new central limit theorem for correlated random variables to show how these models behave in large network settings. They are developing simple algorithms for estimating the key coefficients of the model.

Jackson, together with Bloch and Tebaldi show that although the prominent centrality measures in network analysis make use of different information about

nodes' positions, they all process that information in a very restrictive and identical way. They all spring from a common family that are characterized by the same axioms. In particular, they are all based on an additively separable and linear treatment of a statistic that captures a node's position in the network. Using such statistics on nodes' positions, they also characterize networks on which centrality measures all agree.

List of preprints and publications associated with the grant 2017-18:

Matthew O. Jackson, "[The Friendship Paradox and Systematic Biases in Perceptions and Social Norms](#)," Journal of Political Economy.

Roland Fryer Jr., Philipp Harms, and Matthew O. Jackson, "[Updating Beliefs with Ambiguous Evidence: Implications for Polarization](#)," Journal of the European Economic Association.

Mohammad Akbarpour and Matthew O. Jackson, "[Diffusion in Networks and the Virtue of Burstiness](#)," [Proceedings](#) of the National Academy of Sciences, 115 (30) E6996-E7004, July 24, 2018.

Matthew O. Jackson, Brian Rogers and Yves Zenou, "The Economic Consequences of Social Network Structure," the Journal of Economic Literature, 55:1, 49-95, 2017.

Daron Acemoglu and Matthew O. Jackson, "Social Norms and the Enforcement of Laws," Journal of the European Economic Association, 15:2, 245-295, 2017.

Matthew Leduc, Matthew O. Jackson, and Ramesh Johari, "[Pricing and Referrals in Diffusion on Networks](#)," Games and Economic Behavior, 104, 568-594, 2017.

Jackson, Matthew O. and Xing, Yiqing, The Interaction of Communities, Religion, Governments, and Corruption in the Enforcement of Contracts and Social Norms (July 23, 2018). Available at SSRN: <https://ssrn.com/abstract=3153842> or <http://dx.doi.org/10.2139/ssrn.3153842>

Jackson, Matthew O., A Typology of Social Capital and Associated Network Measures (Mar 21, 2018). Available at SSRN: <https://ssrn.com/abstract=3073496> or <http://dx.doi.org/10.2139/ssrn.3073496>

Jackson, Matthew O. and Storms, Evan, Behavioral Communities and the Atomic Structure of Networks (April 1, 2018). Available at SSRN: <https://ssrn.com/abstract=3049748> or <http://dx.doi.org/10.2139/ssrn.3049748>

Barberà, Salvador and Jackson, Matthew O., A Model of Protests, Revolution, and Information (Aug 1, 2018). Available at SSRN: <https://ssrn.com/abstract=2732864> or <http://dx.doi.org/10.2139/ssrn.2732864>

Bloch, Francis and Jackson, Matthew O. and Tebaldi, Pietro, Centrality Measures in Networks (June 1, 2017). Available at SSRN: <https://ssrn.com/abstract=2749124> or <http://dx.doi.org/10.2139/ssrn.2749124>

Chandrasekhar, Arun G. and Jackson, Matthew O., A Network Formation Model Based on Subgraphs (10 Jul, 2018). Available at SSRN: <https://ssrn.com/abstract=2660381> or <http://dx.doi.org/10.2139/ssrn.2660381>

Banerjee, Abhijit V. and Chandrasekhar, Arun G. and Dufló, Esther and Jackson, Matthew O., Using Gossips to Spread Information: Theory and Evidence from Two Randomized Controlled Trials (21 Mar 2018). MIT Department of Economics Working Paper No. 14-15. Available at SSRN: <https://ssrn.com/abstract=2425379> or <http://dx.doi.org/10.2139/ssrn.2425379>

[P1] Emergence of political change, challenges to law and order

In joint work with Georgy Egorov and Konstantin Sonin, [Social Mobility and the Stability of Democracy: Reevaluating De Tocqueville](#), we revisit the thesis often associated with De Tocqueville which views social mobility as a bulwark of democracy: when members of a social group expect to join the ranks of other social groups in the near future, they should have less reason to exclude these other groups from the political process. In this paper, we investigate this hypothesis using a dynamic model of political economy. As well as formalizing this argument, our model demonstrates its limits, elucidating a robust theoretical force making democracy less stable in societies with high social mobility: when the median voter expects to move up (respectively down), she would prefer to give less voice to poorer (respectively richer) social groups. Our theoretical analysis shows that in the presence of social mobility, the political preferences of an individual depend on the potentially conflicting preferences of her "future selves," and that the evolution of institutions is determined through the implicit interaction between occupants of the same social niche at different points in time. When social mobility is endogenized, our model identifies new political economic forces limiting the amount of mobility in society --- because the middle class will lose out from mobility at the bottom and because a peripheral coalition between the rich and the poor may oppose mobility at the top. This paper is now forthcoming in the *Quarterly Journal of Economics*.

The paper [Democracy Does Cause Economic Growth](#) is an empirical investigation of the effect of political institutions on economic growth. It provides evidence that democracy has a significant and robust positive effect on GDP per capita. Our empirical strategy controls for country fixed effects and the rich dynamics of GDP, which otherwise confound the effect of democracy on economic growth. Moreover, to reduce measurement error, we introduce a new dichotomous measure of democracy that consolidates the information from several sources. Our baseline results use a dynamic panel model for GDP, and show that democratizations increase GDP per capita by about 20% in the long run. We find similar results when we estimate the effect of democratizations on annual GDP, controlling for the GDP dynamics linearly or using the estimated propensity to democratize based on past GDP dynamics. We obtain comparable estimates when we instrument democracy using regional waves of democratizations and reversals. Our results suggest that democracy increases future GDP by encouraging investment, increasing schooling, inducing economic reforms, improving public goods provision, and reducing social unrest. We find little support for the view that democracy is a constraint on economic growth for less developed economies. This paper is now forthcoming in the *Journal of Political Economy*.

A new related paper is [Sustaining Cooperation: Specialized Enforcement Vs. Community Enforcement](#), written joint with Alexander Wolitzky. This paper investigates the related problem of the advantage of formal enforcement in supporting cooperation and other socially desirable behavior as compared to "community enforcement" working in a decentralized fashion. While much of the theoretical literature in game theory focuses on this type of community enforcement (e.g., how norms of good behavior can emerge and

persist because deviations from such a norm, when observed, will start a cascade of deviations ultimately hurting the initial deviator). We depart from this approach by formally introducing specialized enforcers (e.g., law enforcement agents). The main result of our analysis is that, as in many well-functioning societies, the best equilibrium involves only specialized enforcers who punish deviations from prescribed behavior, with no role for community enforcement. Instead, community enforcement is used to discipline specialized enforcers. This result, which is at first surprising, not only coheres with a stylized reading of how many modern societies work, but is also intuitive: though it would be useful to punish deviators both by specialized enforcers and community enforcement, community enforcement would weaken the incentives of specialized enforcers. This is because specialized enforcers themselves are motivated by future rewards to undertake punishment that is not only costly for the deviator but also for themselves. But if they expect a socially costly process of community enforcement, this weakens their incentives. This paper is now completed and submitted for publication.

[P2] Empirical Study of post-conflict Development and political change:

Iraq

Christia spent the year further analyzing data she had collected in Iraq through support from the MURI grant and writing working papers associated with the different projects. Specifically, the Iraq work involved an array of behavioral and network experiments that look at how competing groups as defined by sect, make differential use of their networks to get access to resources, disseminate information across their networks, or make decisions on how to move along contested geographic spaces. There are three distinct experiments and a survey related to this work described briefly below:

Fotini Christia, Dean Knox and Jaffar Al-Rikabi, "Networks of Sectarianism: Experimental Evidence on Access to Services in Baghdad" *working paper*

In a network experiment using cellphones in the highly sectarian context of Baghdad, we show that segregated social networks and different patterns of network searches result in differential levels of access to services between groups. Specifically we find that the politically dominant majority Shia group is substantially less able to access public services than the minority Sunni group. The Shia pursue an inefficient network search strategy that relies on lower-quality contacts, and are less able to leverage their social ties into costly assistance. The minority group appears to have developed better strategies for obtaining resources to which it would otherwise be denied access.

Dean Knox and Fotini Christia. "Geographic Segregation in Baghdad: Detecting Out-group Aversion in Walking Routes." *(have completed the analysis and are presently writing up the paper for submission)*

This project explores how geographic segregation affects Sunni and Shia in their daily lives as they navigate their neighborhoods in Baghdad, using smartphone location-tracking data. We try to explain whether the geographic segregation even among the most-unlikely case

of well-educated youth from the same college/major living near to each other (same city district) is driven by out-group aversion or other structural or behavioral factors.

Fotini Christia, Dean Knox and Elizabeth Dekeyser "The Road to Karbala: Gauging Shia Public Opinion among Religious Iraqis and Iranians."

(have written a 185 page report that we are attaching and two articles showcasing the results in Foreign Affairs and in the Washington Posts' Monkey Cage also attached.

Religious Shiite Iranians and Iraqis arguably form the backbone of support for their respective governments. However, little data is available about their opinions on a range of salient political issues, including the ISIS conflict in Iraq and Syria, Iran's nuclear program, and intra-sectarian conflict in places like Syria, Yemen and Bahrain. We exploited the 2015 Arbaeen pilgrimage to Karbala in South Iraq that brought over 20 million pilgrims, to conduct a survey of 4000 observant Shiites from Iran and Iraq on issues including religion and governance, regional conflict, Iran's nuclear program, and women's rights. The survey uses experiments, including endorsement and conjoint experiments, to elicit truthful responses to highly sensitive political questions.

In "[The nature and Origins of sectarian animosity](#)", Fotini Christia, Dean Knox and Elizabeth Drekeyser ask and answer the following questions: What drives the sectarian antipathy underlying so much conflict across the Middle East? They argue that sectarian animosity stems from a national politicization of sectarian identities. They offer the first systematic, large-scale evaluation of prominent hypotheses about the nature, origins, and content of sectarian antipathy at the individual level. This analysis is based on a broad and geographically representative survey of over 4,000 devout Shi'a from Iraq and Iran, integrated with numerous additional data sources. Their findings suggest tempting parallels between sectarian animosity and ethnonationalism, disillusionment, and lack of out-group contact foster antipathy, nuanced by the uniquely religious aspects of sectarianism. While religious adherence can strongly inflame doctrinal schisms in some social contexts, it moderates tensions in others. they argue that this variation stems from religious socialization, or belief transmission within a religious context to individuals who would otherwise be excluded from the social sphere-a concept that undoubtedly influences not only sectarianism but broader beliefs.

An MIT RA, Elizabeth Dekeyser, who is a PhD candidate in Political Science, got summer support through MURI funding for work related to the Iraq project.

Turkey

Christia also started a project on Turkey with one of my graduate student advisees, Tugba Bozcaga, a PhD candidate in Political Science from Turkey. We are using publicly available data on the over 150,000 purged civil servants and have web scraped and geolocated data on Gulenist schools, financial institutions, and religious endowments in an effort to recreate the degree of influence of that organization over the Turkish bureaucracy and civil service. We are now also in the process of coding the network of the military that

were directly involved in the coup to see how it correlates with the level of Gulenist control of financial and educational institutions across Turkey.

We also did some research on the effect of the German imposed bans of Turkish campaigning among German immigrants in Turkey in support of the “Yes” vote in the Turkish referendum. The findings were reported in the Washington Post’s Monkey Cage (see attached). Tugba Bozcaga got summer support through MURI funding for work related to the Turkey project.

Yemen

CoPI Christia has secured three years worth of cell-phone call records metadata from 2010-2013, which we are using to address the overarching question of how contexts of conflict and violence shape social networks. This project involves PI Jadbabaie, CoPIs Dahleh, and Leskovec. Christia formulates the social science question, Leskovec creates the software infrastructure for the big data analysis, and Dahleh and Jadbabaie, joint with students and postdocs study the network effects.

We have done this collaborative effort by looking at two types of violent events that transpired during this three-year time period: drone strikes that are exogenous violent shocks; and Arab Spring protests that are indigenous to the Yemeni society. (Please note that Google Ideas is very interested in having us over to present and in assisting us with the visualization of our findings once we have things to share.)

We have studied the effect of drone strikes on cellphone communication patterns using three years worth of call and text records from Yemen (2010-2012) and a dated and geolocated dataset of 104 US-induced drone strikes, which includes estimates of civilians and militants killed. We have developed an anomaly detection methodology that detects the effect of strikes on aggregate cellphone activity (volume and direction of calls and texts). We plan to study next the effect of drone strikes on network-level characteristics, and have formed hypotheses to be tested, such as hypotheses related to who people in the area of the strike call and text after the strike.

In terms of drone strikes, we use data on these strikes from the New America Foundation to look at their effect on Yemen’s social network as elicited through patterns of communication captured by cell phone metadata (calls and SMS texts). We are directing our study around three main questions of interest: detecting the effect of drone strikes on cell phone activity; classifying users based on their communication patterns as related to drone strikes; and predicting drone strikes from cell phone activity. Together with coPIs Leskovec and Christia’s research investigated the disruptions of the social network connectivity structure that correlate with the violent events. In particular, they developed a method that allows for identification and localization of violent events through the traces collected from cellphone calls.

We have made some exciting progress studying how revolution displaces people by examining how people from the city move to the countryside at the time of largest unrest

in Yemen.

Fotini Christia, Leon Yao, Stephen Wittels, and Jure Leskovec, "[Yemen Calling: Seven Things Cell Data Reveal About Life In the Republic](#)" *Foreign Affairs*, July 2015

Fotini Christia, Munzer Dahleh, Ali Jadbabaie, Spyros Zypoulis, "Making calls on strikes: call records and drone strikes in Yemen," *NBER Workshop on Economics of National Security*, December 2015

M Freedman, Spyros Zoumpoulis, Fotini Christia and Ali Jadbabaie, "The Effect of Drone Strikes on Civilian Communication: Evidence from Yemen," *American Political Science Review, Revised and Resubmit*, 2019

This project has also led to a novel new method for using call detail records to discover network cascades from data.

Paolo Bertolotti, Ali Jadbabaie, and Fotini Christia, "Tests for Network Cascades via Branching Processes," *IEEE Transactions on network Science and Engineering*, March 2020

[C1,C2] Control of spreading processes

In this thrust we have studied several variations of sequential/networked global games and Extended analysis of social influence over networks[1]:.

Furthermore, Motivated by this work, coPI Ozdaglar and collaborators studied a dynamic policy for the rapid containment of a contagion process modeled as an SIS epidemic on a bounded degree undirected graph with n nodes. They showed that if the budget of curing resources available at each time is lower bounded by the CutWidth of the graph, and also of order $\Omega(\log n)$, then the expected time until the extinction of the epidemic is within a constant factor from optimal, as well as sublinear in the number of nodes. Furthermore, if the CutWidth increases only sublinearly with n , a sublinear expected time to extinction is possible with a sublinearly increasing budget. Furthermore, the authors have characterized network structures under which it is hard to eliminate epidemics[2]

Both of these results have implications on utilizing the network structure to achieve efficient curing policies for epidemics and contagions.

On a different work, Jadbabaie and his postdoc Ajorlou, together with Ozdaglar/Acemoglu's postdoc developed an endogenous model of monopoly dynamic pricing under word of mouth and studied implications of control of an endogenous SI epidemic process (endogenous in the sense that the decision of the agents to spread the word of mouth, depends on the decision of the monopolist in setting the price). The result shows that a strategic monopolist deciding to spread a product/idea among strategic

agents in a network via the word of mouth process, needs to fluctuate the price and bring the price down to its lower bound of zero infinitely often. This is also empirically observed in smartphone app pricing. The analysis is the first to be able to study the implication of word of mouth in a dynamic setting among strategic, forward looking agents, with homophily and word externalities.

Publications

1. K. Drakopoulos, A. Ozdaglar and J. Tsitsiklis, "[When is a network epidemic hard to eliminate?](#)" *Mathematics of Operations Research*, 2017
<http://arxiv.org/abs/1510.06054>
2. Ajorlou, A. Jadbabaie, and A. Kakhbod, "[Dynamic pricing in social networks: The word of Mouth effect,](#)" *Management Science*, 2018
http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2495509

Strategic Analysis of Adversarial Interactions

Acemoglu and Ozdaglar, together with Makhdoumi and Malekian extended the framework first introduced in the recent work of Acemoglu and Ozdaglar which models a network subject to the attack of a virus spreading dynamically over the network. This extension is

motivated by both theoretical considerations and the recent COVID-19 crisis. In particular, in the context of a network model of the spread of a virus, this work introduces voluntary social distancing (as a way of slowing down infections) and testing policy (as a way of identifying infected agents, so that they can be put under isolation). Voluntary social distancing

means that agents decide their own social activity themselves, generating an endogenous social network over which the virus spreads. The paper shows that testing enables the isolation of infected individuals, slowing down infection. But greater testing also reduces voluntary social distancing or increases social activity, exacerbating the spread of the virus. We show that the effects of testing on infections is non-monotone. This non-monotonicity also implies that the optimal testing policy may leave some of the testing capacity of society unused.

D. Acemoglu, A. Malekian, and A. Ozdaglar. Network security and contagion," *Journal of Economic Theory*, 2020.

Acemoglu, D., Makhdoumi, A., Malekian, A., & Ozdaglar, A. (2020). Testing, voluntary social distancing and the spread of an infection (No. w27483). *National Bureau of Economic Research*.