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RPPR Final Report

as of 18-Jan-2023

Agency Code: 21XD

Proposal Number: 67475NSMUR
INVESTIGATOR(S):

Agreement Number: W911NF-15-1-0577

Name: Ph.D. Ambuj Singh
Email: ambuj@cs.ucsb.edu
Phone Number: 8058935283
Principal: Y

Organization: **University of California - Santa Barbara**
Address: 3227 Cheadle Hall, Santa Barbara, CA 931062050
Country: USA

DUNS Number: 094878394

EIN: 956006145W

Report Date: 14-Mar-2022

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Final Report for Period Beginning 15-Sep-2015 and Ending 14-Dec-2021

Title: QUANTA: Quantitative Network-based Models of Adaptive Team Behavior

Begin Performance Period: 15-Sep-2015

End Performance Period: 14-Dec-2021

Report Term: 0-Other

Submitted By: Ph.D. Ambuj Singh

Email: ambuj@cs.ucsb.edu

Phone: (805) 893-5283

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STEM Degrees: 24

STEM Participants: 38

Major Goals: The recent convergence of research in social and psychological sciences, dynamic and quantitative modeling, and network science has led to a re-examination of collective team behavior from a quantitative and systems-oriented viewpoint. Teams cannot be understood fully by studying their components (members) in isolation: team performance is not simply a sum of individual performances; and a diversity of opinions among members leads to better group outcomes. However, it is not yet understood how patterns of interactions and relationships among team members (i.e. team networks) impact performance. Understanding these patterns is critical, as the resolution of complex issues requires deliberative within-group interaction processes in which alternative courses of action are surfaced, evaluated, and acted upon.

Our research will:

- Enable leaders to identify a broader set of strategies for creating successful teams, based on the characteristics of individual members, network structures, and emergent groups;
- Identify processes that enable the emergence of optimal interaction patterns for a given set of individuals or teams, and improve team performance over task sequences;
- Reveal scalable team structures to develop theories and tools for the decomposition of complex tasks;
- Apply machine learning and optimization to identify new approaches that teams and organizations can use to adapt to new and unfamiliar environments.

We propose four research thrusts, broken into sub-tasks:

Thrust 1: Teams as networks of interacting entities (Lead: Singh).

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Our goal is to build quantifiable informative models of teams as dynamical systems interacting over multiple networks.

Task 1.1 Conceptual models for teams and tasks (de la Haye, Friedkin, Malone)

Task 1.2 Statistical and content-based models (Singh, de la Haye)

Task 1.3 Group performance and influence networks (Friedkin, Bullo, Malone)

Task 1.4 Robustness and task assignment (Bullo, Singh)

Thrust 2: Analysis and models of dynamic team behavior. (Lead: Bullo)

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We will analyze dynamic team behavior by developing rigorous models that relate interaction patterns and network evolution to task performance.

Task 2.1 Interpersonal influences on task sequences and evolving networks (Friedkin, Bullo, de la Haye, Uzzi)

RPPR Final Report

as of 18-Jan-2023

Task 2.2 Learning and optimizing dynamic team behavior (Bullo, Friedkin, Malone, Singh)

Thrust 3: Network science of teams of teams and Human+Agent teams. (Lead: Malone)

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We will break new ground in team design by scaling teams to solve complex tasks (i.e. teams of teams), and advancing social science theories of team performance.

Task 3.1 Structure and assignment for nested tasks (Malone, de la Haye, Uzzi)

Task 3.2 Composite models for nested tasks (Bullo, Friedkin, Singh)

Thrust 4: Research into Human-agent Teams

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Following are our project milestones (M.x.x.x.), sorted by task and subtask:

M1.1.1: Years 1-5

Refine the conceptual model of team performance, including properties of the “team space” and “task space”.

M1.1.2: Years 2-3

Develop multilevel models of team performance, identifying individual, network, and group-level predictors using experimental and observational data.

M1.1.3: Years 4-5

Identify the role of “social system smarts” in team performance and strategies for training individuals in this skill.

M1.2.1: Years 1-3

Develop suite of methods for extracting subnetworks that discriminate between teams with varying performance metrics.

M1.2.2: Years 2-4

Develop models of team performance and a characterization of their accuracy on empirical datasets.

M1.2.3: Years 2-3

Develop a method for analyzing transactive memory based on information flows.

M1.2.4: Years 3-5

Extend the developed method from earlier milestones to other measurements of cognitive state of teams.

M1.3.1: Year 1

Advance the measurement models of Collective Intelligence with the construct of combinatorial collective intelligence.

M1.3.2: Year 2

Advance the existing research on the collective intelligence performance linkage by opening the black-box of information integration structure and process by which groups reach their conclusions.

M1.3.3: Years 3-4

Further advance the existing research on the collective intelligence performance linkage with comparisons of intellectual and non-intellectual tasks.

M1.4.1: Years 1-3 (Tarek's. Removed from IPR)

Elaborate on ideas of robustness and resiliency in the framework of teams and tasks.

M1.4.2: Years 4-5 (Tarek. Removed from IPR)

Develop a solution to the team assignment problem using these accomplishments of milestone 1.4.1.

M2.1.1: Year 2

Undertake a study of the collective intelligence-performance linkage among a task sequence. Consider group-level intellectual tasks, with known individual-level task performance biases.

RPPR Final Report as of 18-Jan-2023

M2.1.2: Year 3

Develop a study of the collective intelligence-performance linkage among a task sequence and the comparison of the linkage along task sequences composed of intellective (full information) and non-intellective (withheld information) problems. Advance this work with a consideration of group-level intellective tasks, with known individual-level task biases, and the same tasks converted to a non-intellective form with critical information withheld.

M2.1.3: Years 1-5

Advance the existing research on the collective intelligence performance linkage with comparisons of influence network adaptations in a comparison of task sequences composed of intellective and non-intellective tasks. Provide experiments and field setting analyses that attend to conditions affecting individuals' rational allocation of weights to themselves and others on tasks, and to the effects of external shocks and threats on the expression of CI in influence networks.

M2.2.1: Years 1-2

Develop learning algorithms for sequences of simple intellective task and validate them through experiments with small teams. Learning and optimization along task sequences.

M2.2.2: Years 2-3

Develop strategies for more general control signals, e.g., manipulating micro-interactions and the interpersonal influence network tailored to intellective and non-intellective tasks. Learning for dynamic teams along task sequences.

M2.2.3: Years 3-5

Develop algorithms for dynamic teams based on the models developed for teams in which individual characteristics and network interactions have a dynamics of their own.

M3.1.1: Years 1-5

Decomposition of tasks into subtasks. Provide precise evaluations of different organizational designs in laboratory experiments.

M3.1.2: Years 1-5

Assignment of tasks to individuals and subgroups. Provide detailed formal models of various organizational designs, including analyses of the interactions among:

M3.1.3: Years 1-5

Coordination of interdependencies among subtasks. Conduct detailed field studies of communication and coordination in financial trading organization (and other organizations), including analyses of the relationships among:

M3.2.1: Years 2-5

Develop theories for optimizing the decomposition of teams and tasks and evaluate the methods experimentally.

Add-on Goal: Years 3-5:

Develop an online platform for experimenting with groups and tasks under controlled settings, for research in Human-agent teams.

Accomplishments: From 2015-2021, we maintained steady progress against each of our four proposed research threads. We disseminated results stemming from our research by delivering more than 150 presentations and more than 90 refereed and unrefereed publications. Our publication count includes:

*Journal publications: 58

*Conference publications: 10

*Books: 3

*Book chapters: 6

*Magazine articles: 4

*Dissertations/Theses: 9

*Tech reports: 2

RPPR Final Report as of 18-Jan-2023

In addition, since our last IPR in August 2021, our paper titled “A network formation game for the emergence of hierarchies” was published in PLOS One and two more of our papers have been accepted for publication in 2022. Titles and abstracts for the accepted papers follow:

#Paper 1: Assign and Appraise: Achieving Optimal Performance in Collaborative Teams.

##Abstract: Tackling complex team problems requires understanding each team member's skills in order to devise a task assignment maximizing the team performance. This paper proposes a novel quantitative model describing the decentralized process by which individuals in a team learn who has what abilities, while concurrently assigning tasks to each of the team members. In the model, the appraisal network represents team member's evaluations of one another and each team member chooses their own workload. The appraisals and workload assignment change simultaneously: each member builds their own local appraisal of neighboring members based on the performance exhibited on previous tasks, while the workload is redistributed based on the current appraisal estimates. We show that the appraisal states can be reduced to a lower dimension due to the presence of conserved quantities associated to the cycles of the appraisal network. Building on this, we provide rigorous results characterizing the ability, or inability, of the team to learn each other's skill and thus converge to an allocation maximizing the team performance. We complement our analysis with extensive numerical experiments.

##Citation: Huang, E., Paccagnan, D., Mei, W., Bullo, F. (2022). Assign and Appraise: Achieving Optimal Performance in Collaborative Teams. IEEE Transactions on Automatic Control.

#Paper 2: Predictive Models for Human-AI Nexus in Group Decision-Making.

##Abstract

Machine Learning (ML) and Artificial Intelligence (AI) have had a profound impact on our lives. Domains like health and learning naturally require or are helped by human-AI interactions and decision-making. In these areas, as ML algorithms prove their value in making important decisions, humans add their distinctive expertise and judgment on social and interpersonal issues that need to be considered in tandem with algorithmic inputs of information. Some questions naturally arise. What rules and regulations should be invoked on the employment of AI, and what protocols should be in place to evaluate available AI resources? What are the forms of effective communication and coordination with AI that best promote effective human-AI teamwork? In this review, we highlight factors that we believe are especially important in assembling and managing the human-AI group decision-making.

##Citation: Askarisichani, O., Bullo, F., Friedkin, N.E., and Singh, A. K. (2022). Predictive Models for Human-AI Nexus in Group Decision-Making. Annals of the New York Academy of Sciences.

Finally, we engaged in technology transfer via the release of R packages and the Platform for online Group Studies (POGS 2.0) and collaboration on team dynamics studies with personnel at Fort Bragg. A detailed account of all our accomplishments and advances made on the network science of teams can be found in our expanded final report, appended below.

RPPR Final Report as of 18-Jan-2023

Training Opportunities: We received add-on funds from the Army Educational Opportunities Program (AEOP) to onboard two UC Santa Barbara (UCSB) undergraduate students and one Santa Barbara area high school student for an 8-week summer research experience (June - August 2021). Selected participants would become apprentices to the MURI researchers and join in program activities.

In collaboration with AEOP, MURI participants visited local nearby high school computer science classes and reached out to undergraduate advisors across UCSB. We distributed promotional fliers and fielded questions in an attempt to build interest.

Because of COVID and the remote nature of the program, UCSB undergraduate participation was low. In lieu of a second undergraduate intern, we obtained permission to recruit a second high school student. Our choice UCSB undergraduate accepted a competing internship offer.

Our two high school apprentices had only taken basic programming courses in Java. To bolster their skills, we paired them with participants in a data science boot camp made up of undergraduate students and funded by an NSF program. The boot camp was run by a graduate student in PI Singh's lab and the graduate student who assisted Co-PI Friedkin with the MURI human subjects protocol. Apprentices learned basics of Python programming and machine learning techniques, along with lessons on basic statistics and data visualization. Having formed a bond with the members of the boot camp, the AEOP participants continued for six more weeks with a team-based project in data exploration and analysis.

We encouraged apprentices to participate in weekly skills development classes and lectures hosted by UCSB's Center for Science and Education Partnerships (CSEP), as well as all programmatic activities put forth by AEOP.

Outside of the AEOP opportunity, our MURI's only other training activities involved graduate students in the course of their education and research.

Results Dissemination: MURI participants disseminated results through publications and presentations. We listed a total of 153 presentations throughout our interim reports from 2016-2021. All publications (journal articles, conference presentations, books, etc) are included in the Products section.

RPPR Final Report

as of 18-Jan-2023

Honors and Awards: #2016

Francesco Bullo:

- Guillemin-Cauer Best Paper Award, IEEE Transactions on Circuits & Systems, 2016
- Distinguished Lecturer, IEEE Control Systems Society, 2016-2018
- Distinguished Member Award, IEEE Control Systems Society, December 2015

Kayla de la Haye

- Nominated to the Board of Directors, International Network for Social Network Analysis, June 2016

Brian Uzzi:

- 2016 World Wide Web (WWW) Best Paper Prize (115 submitted papers)
- ASONAM Conference 2016 Keynote Speaker
- Cultures Enterprises Conference, Scotland, 2016 Keynote Speaker
- NetSciX, Poland, 2016 Keynote Speaker
- Rochester U. Conf. Network Diversity & Human Performance, 2016 Keynote Speaker

Young Ji Kim (Postdoc in Malone group):

- Top Paper Award; International Communication Association (Organizational Communication Division), 2016

#2017

Brian Uzzi

- Best Paper Award from WWW
- Keynote Address Ann Sonic Web Science Meeting, Fall 2016 USC
- Article "Make Your Enemies Your Allies: Three steps to reversing a rivalry at work," was reprinted in "How to Work with Toxic Colleagues", Harvard Business Review, August 2016.

Kayla de la Haye:

- Elected to the Board of Directors of the International Network for Social Network Analysis (2017-2020)

Francesco Bullo:

- Distinguished Lecturer, IEEE Control Systems Society, 2016-2018
 - Outstanding Paper Award, IEEE Transactions on Control of Network Systems, 2016
- Article selected for inclusion in 2017 Google Scholar Classic Papers in the area of Automation and Control Theory (top 3 ranking in citation count).
- IFAC Fellow, Class of 2017 "For contributions to network systems and distributed control with application to robotic coordination and power grids."
 - Elected to serve as 2018 President, IEEE Control Systems Society
- Plenary, 14th SIAM Conference on Control & Its Applications, Pittsburgh, PA, USA, Jul 2017
- Plenary, 3rd Indian Control Conference, IIT Guwahati, India, Jan 2017

Ambuj Singh:

- Associate Editor, ACM Transactions on Knowledge Discovery in Data
- Panelist, ANN/SONIC Workshop, March 2017.

Noah Friedkin

- Editor in Chief, Journal of Mathematical Sociology
- Associate Editor, IEEE Transactions on Network Science and Engineering

#2018

Kayla de la Haye:

- 2018 Freeman Award, the International Network for Social Network Analysis (INSNA) bi-annual award for junior scholarship in the study of social structure.

Francesco Bullo:

- Distinguished Scientist Award, PIFI program, Chinese Academy of Sciences.
- Elected IFAC Fellow, Class of 2017. International Federation of Automatic Control (IFAC).

RPPR Final Report

as of 18-Jan-2023

#Noah Friedkin

- Elected AAAS Fellow, American Association for the Advancement of Science (AAAS)

#Brian Uzzi

- Keynote Address at Druid 2018, Copenhagen.
- Keynote Address at Israeli Academy of Management 2018, Tel Aviv.

#2019

Francesco Bullo

- Elected to 2019 Class of Fellows of SIAM
- Distinguished Lecture "Colloquia Roberto Tempo on Automatica," CNR and Politecnico di Torino, Turin, Italy, Apr 2019
- Plenary Lecture: Society of Instrument and Control Engineers Annual Conference, Nara Kasugano, Japan, Sep 2018

Jacqueline Ng Lane

- Finalist for the Best Dissertation Award from the Technology & Innovation Management Division at the Academy of Management 2019 in Boston, MA.

Kayla de la Haye

- Nominated to Executive Committee (Treasurer) of International Network for Social Network Analysis (INSNA)

George Vega Yon

- USC Travel grant for presenting at the 2019 INSNA Sunbelt Conference (\$560 USD)
- Travel grant for form the Society of Young Network Scientists (SYNS) for attending NetSci 2019, Burlington (\$1500 USD)

#2020

Noah Friedkin

- James S Coleman award

#2021

Brain Uzzi

- Elected fellow of the Network Science Society. August 2020.

Protocol Activity Status:

RPPR Final Report

as of 18-Jan-2023

Technology Transfer: #Fort Bragg

PIs de la Haye, Friedkin, and Singh traveled to Fort Bragg on July 30, 2018. They were joined by Edward Palazzolo and Adam Jonas. The goals of the visit were to transfer the MURI research to the 92nd Civilian Affairs Battalion and to conduct some teams of teams experiments. As it turns out, the Fort Bragg structure is ideal for "Teams of Teams" experiments. The 92nd Civilian Affairs Battalion has teams of four with 4-5 teams within a company and 5-6 such companies within the battalion. PIs used this visit to plan running some human subjects experiments on prospect theory.

#Software:

ergmito: The **ergmito** R package implements methods for estimating and analyzing exponential random graph models for small networks using exact statistics. Among the package's functionalities, we have: estimation of pooled models, exact log-likelihood and its gradient, vectorized functions for calculating sufficient statistics on large sets of small networks, simulation of ERGMs using exact statistics, etc. The R package is already available on the MURI GitHub website (<https://github.com/muriteams/ergmito>) and will be shipped to CRAN in August 2019. Authors: George G. Vega Yon, Kayla de la Haye

gnet: An experimental R package built on top of **ergmito** that implements a Monte Carlo test for association between graph level outcomes and network-based statistics such as those used in ERGMs. This is work in progress but can be downloaded from our MURI GitHub website: <https://github.com/muriteams/gnet>. Authors: George G. Vega Yon

similR: This R package implements several different metrics for comparing binary matrices in a vectorized way. The package is mostly based on Krackhardt's work and Choi (2010) survey paper on the issue. This is also available in our GitHub website <https://github.com/muriteams/similR>. Authors: George G. Vega Yon, Kayla de la Haye

George G. Vega Yon, Kayla de la Haye. **ergmito: Exponential Random Graph Models for Small Networks** (2020). R package version 0.3-0. URL: <https://cran.r-project.org/web/packages/ergmito/index.html>
Downloads (7/27/20): 3126

#Platform for Online Group Studies (POGS 2.0)

Singh et al. have continued their work in making POGS 2.0 accessible by a broader research community. They obtained open source licensing (GPL v2) from MIT and UCSB. The software, documentation for developers, and user manual are available on GitHub (<https://github.com/CCI-MIT/POGS>).

PARTICIPANTS:

Participant Type: Co PD/PI

Participant: Tarek Abdelzaher

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Co PD/PI

Participant: Noah Friedkin

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Co PD/PI

RPPR Final Report
as of 18-Jan-2023

Participant: Francesco Bullo
Person Months Worked: 7.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Co PD/PI
Participant: Thomas Malone
Person Months Worked: 2.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Co PD/PI
Participant: Brian Uzzi
Person Months Worked: 3.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Co PD/PI
Participant: Kayla de la Haye
Person Months Worked: 14.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Faculty
Participant: Ge Chen
Person Months Worked: 2.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Faculty
Participant: Young Ji Kim
Person Months Worked: 1.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Faculty
Participant: William Wang
Person Months Worked: 1.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Pushkarini Agharkhar
Person Months Worked: 2.00

Funding Support:

RPPR Final Report
as of 18-Jan-2023

Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Victor Amelkin
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Omid Askarisichari
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Kartikeyan Bajpai
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Ashley Bruce
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Pedro Cisneros
Person Months Worked: 13.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Erik Duhaime
Person Months Worked: 10.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Kevin Gaughan
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

RPPR Final Report
as of 18-Jan-2023

Participant Type: Graduate Student (research assistant)
Participant: Angad Gil
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Nada Hasmi
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Laura Halcomb
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Elizabeth Huang
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Zexi Huang
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Alex Jones
Person Months Worked: 11.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Mert Kosan
Person Months Worked: 8.00 **Funding Support:**
Project Contribution:
National Academy Member: N

RPPR Final Report
as of 18-Jan-2023

Participant Type: Graduate Student (research assistant)
Participant: Arlei Lopes da Silva
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Sourav Medya
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Wenjun Mei
Person Months Worked: 13.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Aneesha Mathur
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Shadi Mohagheghi
Person Months Worked: 13.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Yifatch Nagar
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Jacqueline Ng
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)

RPPR Final Report
as of 18-Jan-2023

Participant: Ashwini Patil

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Janelle Pham

Person Months Worked: 12.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Santha Ramamoorthy

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Mohammad Rasoolinejad

Person Months Worked: 7.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Koa Sato

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Christian Schulz

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Huajie Shao

Person Months Worked: 8.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Shiguang Wang

Person Months Worked: 6.00

Funding Support:

RPPR Final Report
as of 18-Jan-2023

Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Shiguang Wang
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Chandana Uphadhyaya
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: High School Student
Participant: Natalie Fenkner
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: High School Student
Participant: Elliot So
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Non-Student Research Assistant
Participant: Carlos Botelho
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Non-Student Research Assistant
Participant: George Vega Yon
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Other Professional
Participant: Liz McFall
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

RPPR Final Report
as of 18-Jan-2023

Participant Type: Other Professional

Participant: Timothy Robinson

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: PD/PI

Participant: Ambuj Singh

Person Months Worked: 12.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Jennifer Labrecque

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Yeonjeong Kim

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Wei Ye

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Yang Yang

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Julia Poncela-Cassasnovas

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

RPPR Final Report
as of 18-Jan-2023

Participant Type: Undergraduate Student
Participant: Neda Salami
Person Months Worked: 2.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student
Participant: Carrie Scherder
Person Months Worked: 2.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student
Participant: Danielle Shabbouei
Person Months Worked: 1.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student
Participant: Min Jian Yang
Person Months Worked: 1.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student
Participant: Raina Yusfova
Person Months Worked: 1.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Young Ji Kim
Person Months Worked: 15.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Staff Scientist (doctoral level)
Participant: Xuan Hong Dang
Person Months Worked: 7.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student

RPPR Final Report

as of 18-Jan-2023

Participant: Kacie Klein

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

ARTICLES:

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Sociological Sciences

Publication Identifier Type: DOI

Publication Identifier: 10.15195/v3.a20

Volume: 3

Issue:

First Page #: 444

Date Submitted: 8/15/16 12:00AM

Date Published: 6/21/16 7:11PM

Publication Location: United States

Article Title: A Theory of the Evolution of Social Power: Natural Trajectories of Interpersonal Influence Systems along Issue Sequences

Authors: Noah Friedkin, Peng Jia, Francesco Bullo.

Keywords: opinion dynamics; network evolution; influence centrality

Abstract: This article reports new advancements in the theory of influence system evolution in small deliberative groups, and a novel set of empirical findings on such evolution. The theory elaborates the specification of the single-issue opinion dynamics of such groups, which has been the focus of theory development in the field of opinion dynamics, to include group dynamics that occur along a sequence of issues. The theory predicts an evolution of influence centralities along issue sequences based on elementary reflected appraisal mechanisms that modify influence network structure and flows of influence in the group. The new empirical findings, which are also reported in this article, present a remarkable suite of issue-sequence effects on influence network structure consistent with theoretical predictions.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: IEEE Transactions on Network Science and Engineering

Publication Identifier Type: Other

Publication Identifier:

Volume: 3

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First Page #: 286

Date Submitted: 8/30/17 12:00AM

Date Published: 10/2/16 3:48AM

Publication Location:

Article Title: The Coevolution of Appraisal and Influence Networks leads to Structural Balance

Authors: Peng Jia, Noah Friedkin, Francesco Bullo.

Keywords: appraisal evolution, macro-structural models, structural balance theory, mathematical sociology

Abstract: In sociology, an appraisal structure, represented by a signed matrix or a signed network, describes an evaluative cognitive configuration among individuals. In this article we argue that interpersonal influences originate from positive interpersonal appraisals and, in turn, adjust individuals' appraisals of others. This mechanism amounts to a coevolution process of interpersonal appraisals and influences. We provide a mathematical formulation of the coevolutionary dynamics, characterize the invariant appraisal structures, and establish the convergence properties for all possible initial appraisals. Moreover, we characterize the implications of our model to the study of signed social networks. Specifically, our model predicts the convergence of the interpersonal appraisal network to a structure composed of multiple factions with multiple followers. A faction is a group of individuals with positive-complete interpersonal appraisals among them.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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

Journal: Current Directions in Psychological Science

Publication Identifier Type: DOI

Publication Identifier: 10.1177/0963721415599543

Volume: 24

Issue: 6

First Page #: 420

Date Submitted: 8/16/16 12:00AM

Date Published: 8/16/16 8:59PM

Publication Location: United States

Article Title: Collective intelligence and group performance

Authors: Anita Woolley, Ishani Aggarwal, Thomas Malone

Keywords: collective intelligence, group performance, group composition, group, process

Abstract: We review recent research on collective intelligence, which we define as the ability of a group to perform a wide variety of tasks. We focus on two influences on a group's collective intelligence: (a) group composition (e.g., the members' skills, diversity, and intelligence) and (b) group interaction (e.g., structures, processes, and norms). We also call for more research to investigate how social interventions and technological tools can be used to enhance collective intelligence.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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

Journal: Elon Law Journal

Publication Identifier Type: Other

Publication Identifier:

Volume: 9

Issue: 1

First Page #: 116

Date Submitted: 8/31/17 12:00AM

Date Published: 7/17/17 11:05AM

Publication Location:

Article Title: Common Law Evolution and Judicial Impact in the Age of Information

Authors: Ryan Whalen, Satyam Mukherjee, Brian Uzzi

Keywords: Supreme court, Legal Decision Teams, Knowledge networks, Opinion Impact, Legal Decision Impact

Abstract: We show that there are previously undiscovered patterns in the way that common law systems evolve. By focusing on two measures of the age of the references cited in a judicial opinion—reach (average age of cited works) and range (variance of ages cited)—we find that there is one type of citation behavior that is strikingly more likely to be used in highly influential opinions. Cases featuring low reach and high range are more than twice as likely as other types of cases to go on to be highly influential opinions. Evidence for these conclusions are based on three sets of judicial opinions that span a century of time and diverse jurisdictions—the U.S. Supreme Court, the Supreme Court of Canada, and the Supreme Court of India. While these three jurisdictions vary in the way they cite to precedent, the single referencing pattern found to exist behind especially influential cases suggests there is a nearly universal commonality in the evolution of the law.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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

Journal: SIAM Journal on Control and Optimization

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Publication Identifier: 10.1137/16M1065677

Volume: 55

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First Page #: 1280

Date Submitted: 8/30/17 12:00AM

Date Published: 4/28/17 11:49AM

Publication Location:

Article Title: Opinion Dynamics and Social Power Evolution over Reducible Influence Networks

Authors: Peng Jia, Noah Friedkin, Francesco Bullo

Keywords: opinion dynamics, reflected appraisal, influence networks, mathematical sociology, network centrality, dynamical systems, coevolutionary networks

Abstract: In this paper, we extend the analysis of the DeGroot-Friedkin model to two general scenarios where the interpersonal influence network is not necessarily strongly connected and where the individuals form opinions with reducible relative interactions. In the first scenario, the relative interaction digraph is reducible with globally reachable nodes; in the second scenario, the condensation of the relative interaction digraph has multiple aperiodic sinks. For both scenarios, we provide the explicit mathematical formulations of the DeGroot-Friedkin dynamics, characterize their equilibrium points, and establish their asymptotic attractivity properties. This work completes the study of the DeGroot-Friedkin model with most general social network settings and predicts that, under all possible interaction topologies, the emerging social power structures are determined by the individuals' eigenvector centrality scores.

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Acknowledged Federal Support: Y

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

Journal: IEEE Transactions on Automatic Control

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TAC.2017.2694341

Volume: 62

Issue: 11

First Page #: 5650

Date Submitted: 8/29/18 12:00AM

Date Published: 11/2/17 4:08AM

Publication Location:

Article Title: Polar Opinion Dynamics in Social Networks

Authors: Victor Amelkin, Francesco Bullo, Ambuj Singh

Keywords: social networks, opinion dynamics

Abstract: In this work, we propose a general non-linear model of polar opinion dynamics, rooted in several theories of social psychology. The model's key distinguishing trait is that unlike in the existing linear models, such as DeGroot and Friedkin-Johnsen models, the individuals' susceptibility to persuasion is a function of their current opinions. For example, a person holding a neutral opinion may be rather malleable, while "extremists" may be strongly committed to their current beliefs. We also study three specializations of our general model, having different socio-psychological interpretations. We provide a comprehensive theoretical analysis of our non-linear models' behavior using several tools from spectral graph theory, linear algebra, and non-smooth analysis of dynamical systems. To study convergence, we use non-smooth max-min Lyapunov functions together with the generalized Invariance Principle....

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Acknowledged Federal Support: Y

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

Journal: IEEE Transactions on Network Science and Engineering

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TNSE.2017.2651070

Volume: 4

Issue: 2

First Page #: 83

Date Submitted: 8/30/17 12:00AM

Date Published: 4/1/17 7:00AM

Publication Location:

Article Title: Competitive Propagation: Models, Asymptotic Behavior and Quality-Seeding Games

Authors: Wenjun Mei, Francesco Bullo

Keywords: Competitive propagation, independence approximation, network structure, stability analysis, non-cooperative game, seeding, product quality

Abstract: In this paper we propose a class of propagation models for multiple competing products over a social network. We consider two propagation mechanisms: social conversion and self conversion, corresponding, respectively, to endogenous and exogenous factors. A novel concept, the product-conversion graph, is proposed to characterize the interplay among competing products. According to the chronological order of social and self conversions, we develop two Markov-chain models and, based on the independence approximation, we approximate them with two corresponding difference equations systems. Our theoretical analysis on these two approximated models reveals the dependency of their asymptotic behavior on the structures of both the product-conversion graph and the social network, as well as the initial condition. In addition to the theoretical work, we investigate via numerical analysis the accuracy of the independence approximation and the asymptotic behavior of the Markov-chain model....

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Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Science

Publication Identifier Type: DOI

Publication Identifier: 10.1126/science.aag2624

Volume: 354

Issue: 6310

First Page #: 321

Date Submitted: 8/30/17 12:00AM

Date Published: 10/1/16 7:00AM

Publication Location:

Article Title: Network science on belief system dynamics under logic constraints

Authors: Noah E. Friedkin, Anton V. Proskurnikov, Roberto Tempo, Sergey E. Parsegov

Keywords: network science, group influence, consensus

Abstract: Breakthroughs have been made in algorithmic approaches to understanding how individuals in a group influence each other to reach a consensus. However, what happens to the group consensus if it depends on several statements, one of which is proven false? Here, we show how the existence of logical constraints on beliefs affect the collective convergence to a shared belief system and, in contrast, how an idiosyncratic set of arbitrarily linked beliefs held by a few may become held by many.

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Journal: IEEE Transactions on Automatic Control

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TAC.2016.2613905

Volume: 62

Issue: 5

First Page #: 2270

Date Submitted: 8/30/17 12:00AM

Date Published: 5/1/17 7:00AM

Publication Location:

Article Title: Novel Multidimensional Models of Opinion Dynamics in Social Networks

Authors: Sergey E. Parsegov, Anton V. Proskurnikov, Roberto Tempo, Noah E. Friedkin

Keywords: Opinion dynamics, social network, multi-agent system, decentralized algorithm

Abstract: Unlike many complex networks studied in the literature, social networks rarely exhibit unanimous behavior, or consensus. This requires a development of mathematical models that are sufficiently simple to be examined and capture, at the same time, the complex behavior of real social groups, where opinions and actions related to them may form clusters of different size. One such model, proposed by Friedkin and Johnsen, extends the idea of conventional consensus algorithm (also referred to as the iterative opinion pooling) to take into account the actors' prejudices, caused by some exogenous factors and leading to disagreement in the final opinions. In this paper, we offer a novel multidimensional extension, describing the evolution of the agents' opinions on several topics. Unlike the existing models, these topics are interdependent, and hence the opinions being formed on these topics are also mutually dependent. We rigorously examine stability properties of the proposed model....

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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

Journal: ACM Transactions on Internet Technology

Publication Identifier Type: DOI

Publication Identifier: 10.1145/3053371

Volume: 17

Issue: 3

First Page #: 1

Date Submitted: 8/30/17 12:00AM

Date Published: 6/1/17 7:00AM

Publication Location:

Article Title: Experimental Assessment of Aggregation Principles in Argumentation-Enabled Collective Intelligence

Authors: Edmond Awad, Jean-François Bonnefon, Martin Caminada, Thomas W. Malone, Iyad Rahwan

Keywords: collective intelligence, opinion aggregation

Abstract: On the Web, there is always a need to aggregate opinions from the crowd (as in posts, social networks, forums, etc.). Different mechanisms have been implemented to capture these opinions such as Like in Facebook, Favorite in Twitter, thumbs-up/-down, flagging, and so on. However, in more contested domains (e.g., Wikipedia, political discussion, and climate change discussion), these mechanisms are not sufficient, since they only deal with each issue independently without considering the relationships between different claims. We can view a set of conflicting arguments as a graph in which the nodes represent arguments and the arcs between these nodes represent the defeat relation. A group of people can then collectively evaluate such graphs. To do this, the group must use a rule to aggregate their individual opinions about the entire argument graph. Here we present the first experimental evaluation of different principles commonly employed by aggregation rules presented in the

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Journal: arXiv

Publication Identifier Type:

Publication Identifier:

Volume:

Issue:

First Page #:

Date Submitted: 8/30/17 12:00AM

Date Published: 2/8/17 8:00AM

Publication Location:

Article Title: Integrated Information as a Metric for Group Interaction: Analyzing Human and Computer Groups Using a Technique Developed to Measure Consciousness

Authors: David Engel, Thomas W. Malone

Keywords: group interaction, group integration

Abstract: Researchers in many disciplines have previously used a variety of mathematical techniques for analyzing group interactions. Here we use a new metric for this purpose, called integrated information, or ϕ . ϕ was originally developed by neuroscientists as a measure of consciousness in brains, but it captures, in a single mathematical quantity, two properties that are important in many other kinds of groups as well: differentiated ...

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Acknowledged Federal Support: Y

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

Journal: IEEE Transactions on Automatic Control

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TAC.2018.2822182

Volume: 64

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First Page #: 582

Date Submitted: 8/22/19 12:00AM

Date Published:

Publication Location:

Article Title: Social Power Dynamics over Switching and Stochastic Influence Networks

Authors: Ge Chen, Xiaoming Duan, Noah E. Friedkin, Francesco Bullo

Keywords: DeGroot-Friedkin model, stochastic approximation, social networks, social power evolution, opinion dynamics

Abstract: The DeGroot-Friedkin (DF) model is a recently-proposed dynamical description of the evolution of individuals' self-appraisal and social power in a social influence network. Most studies of this system and its variations have so far focused on models with a time-invariant influence network. This paper proposes novel models and analysis results for noisy DF models over stochastically-changing influence networks. First, for a DF model with noise, we show that the trajectory of the social power converges to a ball centered at the equilibrium reached by the original DF model. For such a model with memory, we show that the social power converges to the equilibrium of the original DF model almost surely. Additionally, this paper studies a DF model which is affected by both interaction and environment noise and has memory on the self-appraisal. We show that such a system converges to an equilibrium almost surely. Finally, as a by-product, we provide novel results on the convergence rates....

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Journal: IEEE Transactions on Automatic Control

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Publication Identifier: 10.1109/TAC.2018.2867257

Volume:

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Date Submitted: 8/22/19 12:00AM

Date Published:

Publication Location:

Article Title: Linear Stochastic Approximation Algorithms and Group Consensus over Random Signed Networks

Authors: Ge Chen, Member, Xiaoming Duan, Wenjun Mei, Francesco Bullo

Keywords: stochastic approximation, affine systems, multiagent systems, consensus, signed network

Abstract: This paper studies stochastic approximation models of affine dynamical systems and their application to multi-agent systems in engineering and sociology. As main contribution, we consider stochastic approximation affine dynamics and provide necessary and sufficient conditions for convergence under nonnegative gains, non-positive gains, and arbitrary gains, respectively. We also characterize the system convergence rate, when the system is convergent. Using our general treatment, we provide necessary and sufficient conditions to reach consensus and group consensus for first-order discrete-time multi-agent system over random signed networks and with state-dependent noise. Finally, we extend our results to the setting of multi-dimensional stochastic approximation affine dynamics and characterize the behavior of the multi-dimensional Friedkin-Johnsen model over random interaction networks.

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Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Annual Reviews in Control

Publication Identifier Type: DOI

Publication Identifier: <https://doi.org/10.1016/j.arcontrol.2017.09.00>

Volume: 44

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Date Submitted: 8/29/18 12:00AM

Date Published: 9/28/17 7:00AM

Publication Location:

Article Title: On the Dynamics of Deterministic Epidemic Propagation over Networks

Authors: Wenjun Mei, Shadi Mohagheghi, Sandro Zampieri, Francesco Bullo

Keywords: network propagation model, nonlinear dynamical system, phase transition, mathematical epidemiology

Abstract: In this work we review a class of deterministic nonlinear models for the propagation of infectious diseases over contact networks with strongly-connected topologies. We consider network models for susceptible-infected (SI), susceptible-infected-susceptible (SIS), and susceptible-infected-recovered (SIR) settings. In each setting, we provide a comprehensive nonlinear analysis of equilibria, stability properties, convergence, monotonicity, positivity, and threshold conditions. For the network SI setting, specific contributions include establishing its equilibria, stability, and positivity properties. For the network SIS setting, we review a well-known deterministic model, provide novel results on the computation and characterization of the endemic state (when the system is above the epidemic threshold), and present alternative proofs for some of its properties. Finally, for the network SIR setting, we propose novel results for transient behavior, threshold conditions, stability....

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Journal: IEEE Transactions on Automatic Control

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Volume: 63

Issue: 9

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Date Submitted: 8/29/18 12:00AM

Date Published: 11/20/17 8:00AM

Publication Location:

Article Title: Dynamic Models of Appraisal Networks Explaining Collective Learning

Authors: Wenjun Mei, Noah E. Friedkin, Kyle Lewis, Francesco Bullo

Keywords: collective learning, transactive memory systems, appraisal networks, influence networks, evolutionary games, replicator dynamics, multi-agent systems

Abstract: This paper proposes models of learning process in teams of individuals who collectively execute a sequence of tasks and whose actions are determined by individual skill levels and networks of interpersonal appraisals and influence. The closely-related proposed models have increasing complexity, starting with a centralized manager-based assignment and learning model, and finishing with a social model of interpersonal appraisal, assignments, learning, and influences. We show how rational optimal behavior arises along the task sequence for each model, and discuss conditions of suboptimality. Our models are grounded in replicator dynamics from evolutionary games, influence networks from mathematical sociology, and transactive memory systems from organization science.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: PLOS ONE

Publication Identifier Type: DOI

Publication Identifier: 10.1371/journal.pone.0204547

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Date Submitted: 8/22/19 12:00AM

Date Published:

Publication Location:

Article Title: Dynamics of Collective Performance in Collaboration Networks

Authors: Victor Amelkin, Omid Askarisichani, Young Ji Kim, Thomas W. Malone, Ambuj K. Singh

Keywords: algebraic connectivity, collaboration dynamics, collaboration networks, collective behavior, collective intelligence, collective performance, communication analysis, network analysis, networked teams, optimal workload distribution, organizational science, predictive modeling, regularized regression, sentiment analysis, spectral graph theory, team formation, team performance, team performance dynamics, team performance factors, team performance prediction, team process, teamwork

Abstract: In this study, we extend the existing body of research on team process and prediction models of team performance. Specifically, we analyze the dynamics of historical team performance over a series of tasks as well as the fine-grained patterns of collaboration between team members, and formally connect these dynamics to the team performance in the predictive models. Our major qualitative finding is that higher performing teams have well-connected collaboration networks---as indicated by the topological and spectral properties of the latter---which are more robust to perturbations, and where network processes spread more efficiently. Our major quantitative finding is that our predictive models deliver accurate team performance predictions---with a relative prediction error of 15-25%---on a variety of simple tasks, outperforming baseline models that do not capture the micro-level dynamics of team member behaviors. We also show how to use our models in an application, for the purposes...

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

Journal: American Journal of Sociology

Publication Identifier Type: DOI

Publication Identifier: <https://doi.org/10.1086/692757>

Volume: 123

Issue: 2

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Date Submitted: 8/29/18 12:00AM

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Publication Location:

Article Title: The Structural Balance Theory of Sentiment Networks: Elaboration and Test

Authors: Craig Rawlings, Noah Friedkin

Keywords: balance theory; sentiment networks

Abstract: Structural balance theory attends to a group's network of sentiments and posits that this network alters over time toward particular structural forms. Current work on the theory is focused on understanding the mechanisms that alter sentiments as a function of the configuration of sentiments in which they are embedded. Although the theory assumes tension reduction mechanisms, there has been no effort to directly measure and model the temporal changes of individuals' relational tensions that are predicted by the theory. This article elaborates and tests balance theory with an empirical analysis of its posited interpersonal tensions and their reductions via a sentiment conversion process. In addition, the authors open a new line of inquiry on the theory's scope conditions and point to a community commitment condition that is involved in the realization of structural balance. Their analysis draws on a unique suite of multiwave measures obtained from the Urban Communes Data Set.

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Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Science Advances

Publication Identifier Type: DOI

Publication Identifier: 10.1126/sciadv.1601315

Volume: 3

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Date Submitted: 8/30/17 12:00AM

Date Published: 4/1/17 7:00AM

Publication Location:

Article Title: The nearly universal link between the age of past knowledge and tomorrow's breakthroughs in science and technology: The hotspot

Authors: Satyam Mukherjee, Daniel M. Romero, Ben Jones, Brian Uzzi

Keywords: Social networks, Knowledge networks, computational social science, science of science, scientometrics, human performance

Abstract: Scientists and inventors can draw on an ever-expanding literature for the building blocks of tomorrow's ideas, yet little is known about how combinations of past work are related to future discoveries. Our analysis parameterizes the age distribution of a work's references and revealed three links between the age of prior knowledge and hit papers and patents. First, works that cite literature with a low mean age and high age variance are in a citation "hotspot"; these works double their likelihood of being in the top 5% or better of citations. Second, the hotspot is nearly universal in all branches of science and technology and is increasingly predictive of a work's future citation impact. Third, a scientist or inventor is significantly more likely to write a paper in the hotspot when they are coauthoring than when they are working alone. Our findings are based on all 28,426,345 scientific papers in the Web of Science, 1945–2013, and all 5,382,833 U.S. patents, 1950–2010....

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RPPR Final Report as of 18-Jan-2023

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

Journal: Transactions on the Web (TWEB)

Publication Identifier Type: DOI

Publication Identifier: 10.1145/3295460

Volume: 13

Issue: 1

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Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: Social Networks under stress: Specialized Team Roles and their Communication Structure

Authors: Daniel Romero, Brian Uzzi, Jon Kleinberg

Keywords: Social Networks, Organizations, Temporal Dynamics, Collective Behavior

Abstract: Social network research has begun to take advantage of fine-grained communications regarding coordination, decision-making, and knowledge sharing. These studies, however, have not generally analyzed how external events are associated with a social network's structure and communicative properties. Here, we study how external events are associated with a network's change in structure and communications. Analyzing a complete dataset of millions of instant messages among the decision-makers in a large hedge fund and their network of outside contacts, we investigate the link between price shocks, network structure, and change in the affect and cognition of decision-makers embedded in the network. When price shocks occur the communication network tends not to display structural changes associated with adaptiveness...

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Nature Human Behavior

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41562-018-0460-y

Volume: 3

Issue: 1

First Page #: 74

Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: Prior shared success predicts victory in team competitions

Authors: Satyam Mukherjee, Yun Huang, Julia Neidhart, Brian Uzzi, Noshir Contractor

Keywords: team sports, network science, moneyball, intra-team relationships

Abstract: The debate about the impact of team configurations on the outcome of a contest has attracted sports enthusiasts and sports scientists for years. A common belief of team success is the superstar effect, i.e., including more talent improves team performance. On the other hand, relationships among team members play a key role in providing a competitive advantage for one team over its opponent. Studies on team sports suggest that previous relations and shared experience among team members improve the mutual understanding of individual habits, techniques, and abilities and therefore enhance team coordination. This study explores the impact of within-team relationships on the outcome of competitions between sports teams. We examine this effect using the historical records of four professional sports, basketball in the National Basketball Association (NBA), soccer in the English Premier League (EPL), cricket in the India Premier League (IPL), and baseball in Major League Baseball (MLB), ...

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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

Journal: Harvard Business Review

Publication Identifier Type:

Publication Identifier:

Volume: Issue:

First Page #:

Date Submitted: 8/30/18 12:00AM

Date Published:

Publication Location:

Article Title: How to Find the Hotspots for Your Next Breakthrough Idea

Authors: Brian Uzzi and Ben Jones

Keywords: network science, scientific web, information impact

Abstract: We studied 5.4 million U.S. patents from 1950-2010 and all 28.4 million scientific papers on the Web of Science over the period from 1945 to 2013. The Web of Science and U.S. Patent Office Database are among the world's largest known repositories for scientific research and technology innovations, respectively. Specifically, we looked at two things. The first was the impact the patent or paper in question had, measured by how many times it had been cited in other works. The number of citations a given patent garners, for example, has been tied to its economic returns, such as the market share of products based on related technology. The second was the age of information those papers and patents drew on, in terms of both the average and spread of ages. These two factors were consistent in scientific research, patents, and law (based on our study of Supreme Court rulings in the U.S., Canada, and India).

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Acknowledged Federal Support: Y

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

Journal: Harvard Business Review (as a reprint in "How to Work with Toxic Colleagues")

Publication Identifier Type:

Publication Identifier:

Volume: Issue:

First Page #:

Date Submitted: 8/31/17 12:00AM

Date Published: 8/31/16 4:04PM

Publication Location:

Article Title: Make Your Enemies Your Allies: Three steps to reversing a rivalry at work

Authors: Brian Uzzi and Shannon Dunlap

Keywords: team building, group dynamics, collective behavior, psychology of influence

Abstract: The authors introduce the three R's (Redirection, Reciprocity, and Rationality) as methods for culling rivalries in a team environment. The method is drawn from the authors' own inductive case studies—including interviews with business leaders such as John Clendenin, who agreed to let us tell his story in this article—and from empirical research conducted by Brian and others investigating the physiology of the brain, the sociology of relationships, and the psychology of influence.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

RPPR Final Report as of 18-Jan-2023

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Social Networks

Publication Identifier Type: DOI

Publication Identifier: 10.1016/j.socnet.2017.02.001

Volume: 50

Issue:

First Page #: 17

Date Submitted: 8/29/18 12:00AM

Date Published: 7/1/17 7:00AM

Publication Location:

Article Title: Analytic strategies for longitudinal networks with missing data

Authors: Kayla de la Haye, Joshua Embree, Marc Punkay, Dorothy L. Espelage, Joan S. Tucker, Harold D. Green

Keywords: Longitudinal analysis, Social networks, Stochastic actor-based model, SIENA, Analytic sample, Friendship network

Abstract: Missing data are often problematic when analyzing complete longitudinal social network data. We review approaches for accommodating missing data when analyzing longitudinal network data with stochastic actor-based models. One common practice is to restrict analyses to participants observed at most or all time points, to achieve model convergence. We propose and evaluate an alternative, more inclusive approach to sub-setting and analyzing longitudinal network data, using data from a school friendship network observed at four waves (N = 694). Compared to standard practices, our approach retained more information from partially observed participants, generated a more representative analytic sample, and led to less biased model estimates for this case study. The implications and potential applications for longitudinal network analysis are discussed.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Proceedings of the National Academy of Sciences

Publication Identifier Type: DOI

Publication Identifier: 10.1073/pnas.1710603114

Volume: 114

Issue: 43

First Page #: 11380

Date Submitted: 8/29/18 12:00AM

Date Published: 10/1/17 7:00AM

Publication Location:

Article Title: How truth wins in opinion dynamics along issue sequences

Authors: Noah E. Friedkin, Francesco Bullo

Keywords: network science, opinion dynamics, truth statements

Abstract: How truth wins in social groups is an important open problem. Classic experiments on social groups dealing with truth statement issues present mixed findings on the conditions of truth abandonment and reaching a consensus on the truth. No theory has been developed and evaluated that might integrate these findings with a mathematical model of the interpersonal influence system that alters some or all of its members' positions on an issue. In this paper we provide evidence that a general model in the network science on opinion dynamics substantially clarifies how truth wins in groups.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IFAC-PapersOnLine
Publication Identifier Type: DOI **Publication Identifier:** 10.1016/j.ifacol.2017.08.1424
Volume: 50 **Issue:** 1 **First Page #:** 11896
Date Submitted: 9/6/18 12:00AM **Date Published:** 7/1/17 2:00PM
Publication Location:

Article Title: Opinion evolution in time-varying social influence networks with prejudiced agents

Authors: Anton V. Proskurnikov, Roberto Tempo, Ming Cao, Noah E. Friedkin

Keywords: social influence dynamics, social networks, Friedkin-Johnson model

Abstract: Investigation of social influence dynamics requires mathematical models that are “simple” enough to admit rigorous analysis, and yet sufficiently “rich” to capture salient features of social groups. Thus, the mechanism of iterative opinion pooling from (DeGroot, 1974), which can explain the generation of consensus, was elaborated in (Friedkin and Johnsen, 1999) to take into account individuals’ ongoing attachments to their initial opinions, or prejudices. The “anchorage” of individuals to their prejudices may disable reaching consensus and cause disagreement in a social influence network. Further elaboration of this model may be achieved by relaxing its restrictive assumption of a time-invariant influence network. During opinion dynamics on an issue, arcs of interpersonal influence may be added or subtracted from the network, and the influence weights assigned by an individual to his/her neighbors may alter. In this paper, we establish new important properties of the (Friedkin and John

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Science
Publication Identifier Type: DOI **Publication Identifier:** 10.1126/science.aao0185
Volume: 359 **Issue:** 6379 **First Page #:**
Date Submitted: 8/31/18 12:00AM **Date Published:** 3/1/18 4:00PM
Publication Location:

Article Title: Science of science

Authors: Santo Fortunato, Carl T. Bergstrom, Katy Börner, James A. Evans, Dirk Helbing, Staša Milojević, Alexar

Keywords: network science; science

Abstract: Identifying fundamental drivers of science and developing predictive models to capture its evolution are instrumental for the design of policies that can improve the scientific enterprise — for example, through enhanced career paths for scientists, better performance evaluation for organizations hosting research, discovery of novel effective funding vehicles, and even identification of promising regions along the scientific frontier. The science of science uses large-scale data on the production of science to search for universal and domain-specific patterns. Here, we review recent developments in this transdisciplinary field.

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Acknowledged Federal Support: Y

RPPR Final Report as of 18-Jan-2023

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

Journal: Review of Economics and Statistics

Publication Identifier Type: DOI

Publication Identifier: 10.1162/rest_a_00780

Volume: 101

Issue: 3

First Page #:

Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: The Reverse Matthew Effect: Consequences of Retraction in Scientific Teams

Authors: Ginger Zhe Jin, Benjamin Jones, Susan Feng Lu, Brian Uzzi

Keywords: teamwork, reward, reputation, information , science, retraction, Matthew Effect

Abstract: Teamwork pervades modern production and organizations, yet teamwork can make individual roles difficult to ascertain. In assigning individual rewards, the "Matthew Effect" suggests that communities presume eminent team members are responsible for great outcomes, reducing the credit that accrues to less eminent team members. We study this phenomenon in reverse, investigating credit sharing for damaging events. Our empirical context is article retractions in the sciences and the effect these negative events impose on citations to the authors' prior work. We find that retractions impose little citation penalty on eminent coauthors, but less eminent coauthors face substantial citation declines, especially when teamed with an eminent author. These findings suggest a "Reverse Matthew Effect" for team-produced negative events. A Bayesian model provides a candidate interpretations.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 4-Under Review

Journal: Network Science

Publication Identifier Type:

Publication Identifier:

Volume:

Issue:

First Page #:

Date Submitted: 8/28/19 12:00AM

Date Published:

Publication Location:

Article Title: Social intelligence and social networks predict group performance.

Authors: Jennifer Labrecque, Young Ji Kim, Thomas W. Malone, George G Vega Yon, Kayla de la Haye

Keywords: Emotional Intelligence, Individual Differences, Network theory, Networks, Social Network Analysis, Research Methods

Abstract: Investigations of group performance have traditionally focused on cognitive ability and skill; however, recent studies have identified social abilities as important predictors of performance. In this exploratory study, we investigate whether multiple social ability domains will influence group performance, either directly by allowing the group to work together effectively to complete the task, or indirectly by shaping group social network structures that influence performance capacity. We tested this relationship using an experimental design in which 42 mixed-gender groups of three to five participants worked together on problem-solving tasks and individually completed social intelligence assessments. We also assessed group influence and leadership networks, and identified their structural features (e.g., density). We found that social intelligence influenced group performance through both of the proposed pathways: a direct path in which greater diversity on some social abilities....

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Acknowledged Federal Support: Y

RPPR Final Report as of 18-Jan-2023

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

Journal: IEEE Transactions on Network Science and Engineering

Publication Identifier Type: DOI

Publication Identifier: 10.1137/18M1232267

Volume: 58

Issue: 2

First Page #: 639

Date Submitted: 8/4/20 12:00AM

Date Published:

Publication Location:

Article Title: Finite-time wisdom of crowds and naive learning

Authors: Francesco Bullo, Fabio Fagnani, B. Franci

Keywords: opinion dynamics, influence systems, wisdom of crowd, learning

Abstract: Recent contributions have studied how an influence system may affect the wisdom of crowd phenomenon. In the so-called naive learning setting, a crowd of individuals holds opinions that are statistically independent estimates of an unknown parameter; the crowd is wise when the average opinion converges to the true parameter in the limit of infinitely many individuals. Unfortunately, even starting from wise initial opinions, a crowd subject to certain influence systems may lose its wisdom. It is of great interest to characterize when an influence system preserves the crowd wisdom effect. In this paper we introduce and characterize numerous wisdom preservation properties of the basic French-DeGroot influence system model. Instead of requiring complete convergence to consensus as in the previous naive learning model by Golub and Jackson, we study finite-time executions of the French-DeGroot influence process and establish in this novel context the notion of prominent families...

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Acknowledged Federal Support: Y

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

Journal: Journal of Nature Communications

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41467-019-10548-8

Volume: 10

Issue:

First Page #:

Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: Structural balance emerges and explains performance in risky decision-making

Authors: Omid Askarisichani, Jacqueline Ng, Francesco Bullo, Noah E. Friedkin, Ambuj K. Singh, and Brian Uzzi

Keywords: Emotional Intelligence, Individual Differences, Network theory, Networks, Social Network Analysis, Research Methods

Abstract: Polarization affects many forms of social organization. A key issue focuses on which affective relationships are prone to change and how their change relates to performance. In this study, we analyze a financial institutional over a two-year period that employed 66 day traders, focusing on links between changes in affective relations and trading performance. Traders' affective relations were inferred from their IMs (>2 million messages) and trading performance was measured from profit and loss statements (>1 million trades). Here, we find that triads of relationships, the building blocks of larger social structures, have a propensity towards affective balance, but one unbalanced configuration resists change. Further, balance is positively related to performance. Traders with balanced networks have the "hot hand", showing streaks of high performance. Research implications focus on how changes in polarization relate to performance and polarized states can depolarize.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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RPPR Final Report as of 18-Jan-2023

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

Journal: Automatica

Publication Identifier Type: DOI

Publication Identifier: 10.1016/j.automatica.2019.108580

Volume: 110

Issue:

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Date Submitted: 8/4/20 12:00AM

Date Published:

Publication Location:

Article Title: Dynamic social balance and convergent appraisals via homophily and influence mechanisms

Authors: Wenjun Mei, Pedro Cisneros-Velarde, Noah E. Friedkin, Francesco Bullo

Keywords: structural balance; nonlinear dynamics; homophily; influence system; faction formation; multi-agent systems

Abstract: Recent contributions have studied how an influence system may affect the wisdom of crowd phenomenon. In the so-called naive learning setting, a crowd of individuals holds opinions that are statistically independent estimates of an unknown parameter; the crowd is wise when the average opinion converges to the true parameter in the limit of infinitely many individuals. Unfortunately, even starting from wise initial opinions, a crowd subject to certain influence systems may lose its wisdom. It is of great interest to characterize when an influence system preserves the crowd wisdom effect. In this paper we introduce and characterize numerous wisdom preservation properties of the basic French-DeGroot influence system model. Instead of requiring complete convergence to consensus as in the previous naive learning model by Golub and Jackson, we study finite-time executions of the French-DeGroot influence process and establish in this novel context the notion of prominent families...

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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.2019.2951672

Volume: 7

Issue: 2

First Page #:

Date Submitted: 8/6/20 12:00AM

Date Published:

Publication Location:

Article Title: Opinion dynamics and social power evolution; A single-timescale model

Authors: Peng Jia, Noah E. Friedkin, Francesco Bullo

Keywords: social networks

Abstract: This paper studies the evolution of self-appraisal and social power, for a group of individuals who discuss and form opinions. We consider a modification of the recently proposed DeGroot-Friedkin (DF) model, in which the opinion formation process takes place on the same timescale as the reflected appraisal process; we call this new model the single-timescale DF model. We provide a comprehensive analysis of the equilibria and convergence properties of the model for the settings of irreducible and reducible influence networks. For the setting of irreducible influence networks, the single-timescale DF model has the same behavior as the original DF model, that is, it predicts among other things that the social power ranking among individuals is asymptotically equal to their centrality ranking, that social power tends to accumulate at the top of the centrality ranking hierarchy, and that an autocratic (resp., democratic) power structure arises when the centrality scores are maximally ...

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

Journal: Science

Publication Identifier Type: DOI

Publication Identifier: 10.1073/pnas.1721438116

Volume: 116

Issue: 6

First Page #:

Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: A network's gender composition and communication pattern predict women's leadership success

Authors: Yang Yand, Nitesh V. Chawla, Brian Uzzi

Keywords: Gender Inequality, STEM Leadership, Social Network, QED, Computational Social Science

Abstract: Leaders in STEM fields influence the careers of all STEM professionals, yet little research exists on how STEM leadership jobs are obtained. Many leaders in STEM are now recruited directly out of graduate programs that provide advanced technical and managerial training. Here, we use a quasi-experiment to better understand the relationship between graduate school and direct placement into STEM leadership positions. Our data includes information on the individual characteristics and social networks of hundreds of students in a program that places its graduates directly into STEM leadership positions. We find that sex differences in students' social networks predict placement in STEM leadership positions. High-placing women's networks have an inner circle that incorporates an uncommon duality. High-placing women's networks are both cliquish and diverse. They are cliquish in terms of gender homophily and communication patterns, while, at the same time, each female contact accesses a ...

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Acknowledged Federal Support: Y

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

Journal: Network Science

Publication Identifier Type: DOI

Publication Identifier: <https://doi.org/10.1017/nws.2019.22>

Volume: 7

Issue: 4

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Date Submitted: 8/6/20 12:00AM

Date Published:

Publication Location:

Article Title: Multi-Group Connectivity Structures and their Implications

Authors: Shadi Mohagheghi, Pushkarini Agharkar, Noah E. Friedkin, Francesco Bullo

Keywords: multi-groups networks, connectivity modalities, random graphs, comparative analysis

Abstract: We investigate the implications of different forms of multi-group connectivity. Four multi-group connectivity modalities are considered: co-memberships, edge bundles, bridges, and liaison hierarchies. We propose generative models to generate these four modalities. Our models are variants of planted partition or stochastic block models conditioned under certain topological constraints. We report findings of a comparative analysis in which we evaluate these structures, controlling for their edge densities and sizes, on mean rates of information propagation, convergence times to consensus, and steady state deviations from the consensus value in the presence of noise as network size increases.

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

Journal: Scientific Reports

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41598-018-37847-2

Volume: 9

Issue:

First Page #:

Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: Mathematical Structures in Group Decision-Making on Resource Allocation Distributions

Authors: Noah E. Friedkin, Wenjun Mei, Anton V. Proskurnikov, and Francesco Bullo

Keywords: Social Networks

Abstract: In this article, we investigate group decision-making on resource allocations distributions under conditions of uncertainty that disallow an ascertainable optimum decision. We show that a group's array of initial opinions sets up a geometric decision space of alternative resource distributions, that a group's final opinion(s) are usually constrained to this initial decision space, and that weighted averaging opinion update dynamics is predictive of the final opinion(s). With informally generated decision spaces and heuristic searches for an agreed upon distribution within these decision spaces, our evidence points to a natural form of bounded rationality that is related but not equivalent to formal optimization procedures.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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

Journal: PLOS-One

Publication Identifier Type: DOI

Publication Identifier: 10.1371/journal.pone.0205335

Volume: 13

Issue: 10

First Page #:

Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: Integrated information as a metric for group interaction: Analyzing human and computer groups using a technique developed to measure consciousness. .

Authors: David Engel, Thomas W. Malone

Keywords: phi, collective intelligence, group consensus

Abstract: Researchers in many disciplines have previously used a variety of mathematical techniques for analyzing group interactions. Here we use a new metric for this purpose, called "integrated information" or "phi." Phi was originally developed by neuroscientists as a measure of consciousness in brains, but it captures, in a single mathematical quantity, two properties that are important in many other kinds of groups as well: differentiated information and integration. Here we apply this metric to the activity of three types of groups that involve people and computers. First, we find that 4-person work groups with higher measured phi perform a wide range of tasks more effectively, as measured by their collective intelligence. Next, we find that groups of Wikipedia editors with higher measured phi create higher quality articles. Last, we find that the measured phi of the collection of people and computers communicating on the Internet increased over a recent six-year period. Together...

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

RPPR Final Report as of 18-Jan-2023

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

Journal: Proceedings of the National Academy of Science (PNAS)

Publication Identifier Type: DOI

Publication Identifier: 10.1073/pnas.1800485115

Volume: 115

Issue: 50

First Page #:

Date Submitted: 8/27/19 12:00AM

Date Published:

Publication Location:

Article Title: The Scientific Prize Network Predicts Who Pushes the Boundaries of Science

Authors: Yifeng Ma, Brian Uzzi

Keywords: scientific prizes, funding, networks

Abstract: Scientific prizes are among the greatest recognitions a scientist receives from their peers and arguably shape the direction of a field by conferring credibility to persons, ideas, and disciplines, providing financial rewards, and promoting rituals that reinforce scientific communities. Though debates continue about prizes' overall benefits to science, prizes in science have proliferated. Thousands of prizes are now awarded across diverse sciences, topics, regions of the world, and for different levels of scientific discovery. The proliferation of prizes and links among prizes suggest that the prize network embodies information about scientists and ideas poised to grow in acclaim. Using comprehensive new data on prizes and prizewinners worldwide and across disciplines, we examine the growth dynamics and interlocking relationships found in the worldwide scientific prize network. We focus on understanding how the knowledge linkages among prizes ...

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: N

Publication Status: 1-Published

Journal: Harvard Business Review

Publication Identifier Type:

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Volume:

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First Page #:

Date Submitted: 9/10/18 12:00AM

Date Published: 7/20/18 2:00PM

Publication Location:

Article Title: A Study of Thousands of Dropbox Projects Reveals How Successful Teams Collaborate.

Authors: Adam Pah, Brian Uzzi, Rebecca Hinds

Keywords: DropBox, collaboration, team work

Abstract: Researchers anonymized Dropbox data on 500,000 projects involving 400,000 users at 1,000 universities and compared the collaborative dynamics they saw against the research performance of those institutions. They uncovered five best practices for effective teamwork on file-sharing platforms: use small teams, don't rush projects, increase same-team collaborations, share work equally, and include experienced collaborators.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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

Journal: Science

Publication Identifier Type:

Publication Identifier:

Volume: 361

Issue: 6408

First Page #:

Date Submitted: 8/27/19 12:00AM

Date Published: 9/21/18 2:00PM

Publication Location:

Article Title: Novelty, Hotspots, and Knowledge Recombination

Authors: Brian Uzzi, Dashun Wang

Keywords: scientific impact

Abstract: Recent research on nearly 27 million scientific papers since 1950, and more than 5 million U.S. patents since 1970, shows that how scientists sample the ever-expanding literature is critical to making breakthroughs, irrespective of discipline. First, papers or patents that cite literature of a certain age range (mean of about 5 years, with a high variance) are roughly twice as likely to be a hit (in the top 5% of citations) than a field's average paper. By contrast, the 75% of papers and patents that combine knowledge from outside this "hotspot," referencing the most popular or most recent literature—work commonly sampled by search engines—are not particularly likely to be hits. Second, hit papers mix highly typical and highly novel ideas and do so roughly according to a 90/10 ratio. Such papers referencing highly familiar knowledge—literature that historically has been cited together much more frequently than expected by chance—while at the same time citing papers that have rarely....

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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

Journal: PNAS

Publication Identifier Type: DOI

Publication Identifier: 10.1073/pnas.1909046117

Volume: 117

Issue: 20

First Page #: 10762

Date Submitted: 8/6/20 12:00AM

Date Published:

Publication Location:

Article Title: Estimating the deep replicability of scientific findings using human and artificial intelligence

Authors: Youyou Wu, Yang Yang, Brian Uzzi

Keywords: replicability, machine learning, computational social science

Abstract: Replicability tests of scientific papers show that the majority of papers fail replication. Moreover, failed papers circulate through the literature as quickly as replicating papers. This dynamic weakens the literature, raises research costs, and demonstrates the need for new approaches for estimating a study's replicability. Here, we trained an artificial intelligence model to estimate a paper's replicability using ground truth data on studies that had passed or failed manual replication tests, and then tested the model's generalizability on an extensive set of out-of-sample studies. The model predicts replicability better than the base rate of reviewers and comparably as well as prediction markets, the best present-day method for predicting replicability. In out-of-sample tests on manually replicated papers from diverse disciplines and methods, the model had strong accuracy levels of 0.65 to 0.78....

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RPPR Final Report as of 18-Jan-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Frontiers in Psychology
Publication Identifier Type: DOI **Publication Identifier:** 10.3389/fpsyg.2019.00112
Volume: **Issue:** **First Page #:**
Date Submitted: 8/27/19 12:00AM **Date Published:** 2/8/19 8:33AM
Publication Location:

Article Title: The Impact of Cognitive Style Diversity on Implicit Learning in Teams

Authors: Ishani Aggarwal, Anita Williams Woolley, Christopher F. Chabris, Thomas W. Malone

Keywords: teams, team learning, implicit coordination, collective intelligence, cognitive diversity

Abstract: Organizations are increasingly looking for ways to reap the benefits of cognitive diversity for problem solving. A major unanswered question concerns the implications of cognitive diversity for longer-term outcomes such as team learning, with its broader effects on organizational learning and productivity. We study how cognitive style diversity in teams—or diversity in the way that team members encode, organize and process information—indirectly influences team learning through collective intelligence, or the general ability of a team to work together across a wide array of tasks. Synthesizing several perspectives, we predict and find that cognitive style diversity has a curvilinear—inverted U-shaped—relationship with collective intelligence. Collective intelligence is further positively related to the rate at which teams learn, and is a mechanism guiding the indirect relationship between cognitive style diversity and team learning. We test the predictions in 98 teams using ...

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: ACM Transactions on Knowledge Discovery from Data
Publication Identifier Type: DOI **Publication Identifier:** 10.1145/3332168
Volume: 13 **Issue:** 4 **First Page #:** 1
Date Submitted: 8/28/19 12:00AM **Date Published:** 8/1/19 7:00AM
Publication Location:

Article Title: A Distance Measure for the Analysis of Polar Opinion Dynamics in Social Networks

Authors: Victor Amelkin, Petko Bogdanov, Ambuj K. Singh

Keywords: anomaly detection, competing opinions, distance measure, Earth Mover's Distance, minimum-cost network flow., model-driven analysis, opinion dynamics, opinion prediction, polar opinions, polarization, social network, time-series, transportation problem, Wasserstein metric

Abstract: Analysis of opinion dynamics in social networks plays an important role in today's life. For predicting users' political preference, it is particularly important to be able to analyze the dynamics of competing polar opinions, such as pro-Democrat vs. pro-Republican. While observing the evolution of polar opinions in a social network over time, can we tell when the network evolved abnormally? Furthermore, can we predict how the opinions of the users will change in the future? To answer such questions, it is insufficient to study individual user behavior, since opinions can spread beyond users' ego-networks. Instead, we need to consider the opinion dynamics of all users simultaneously and capture the connection between the individuals' behavior and the global evolution pattern of the social network. In this work, we introduce the Social Network Distance (SND)---a distance measure that quantifies the likelihood of evolution of one snapshot ...

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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

Journal: Dynamic Games and Applications

Publication Identifier Type: DOI

Publication Identifier: 10.1007/s13235-019-00346-8

Volume:

Issue:

First Page #:

Date Submitted: 8/6/20 12:00AM

Date Published:

Publication Location:

Article Title: Signed Network Formation Games and Clustering Balance

Authors: Pedro Cisneros-Velarde, Francesco Bullo

Keywords: network formation, balance theory, clustering balance

Abstract: We propose a signed network formation game, in which pairs of individuals strategically change the signs of the edges in a complete network. These individuals are members of a social network who strategically reduce cognitive dissonances by changing their interpersonal appraisals. We characterize the best-response dynamics for this game and prove that its implementation can dynamically drive the network to a sociologically meaningful sign configuration called clustering balance. In this configuration, agents in the social network form one or more clusters that have positive relationships among their members but negative relationships among members of other clusters. In the past, various researchers in the fields of psycho-sociology, political science, and physics have looked at models that explain the generation of up to two clusters. Our work contributes to these fields by proposing a simple model that generates a broader class of signed networks.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Automatica

Publication Identifier Type: DOI

Publication Identifier: 10.1016/j.automatica.2020.108825

Volume: 114

Issue:

First Page #: 108825

Date Submitted: 8/6/20 12:00AM

Date Published:

Publication Location:

Article Title: Convergence Properties of the Heterogeneous Deffuant-WeisbuchModel

Authors: Ge Chen, Wei Su, Wenjun Mei, Francesco Bullo

Keywords: Opinion dynamics, consensus, Deffuant model, gossip model, bounded confidence model

Abstract: We propose a signed network formation game, in which pairs of individuals strategically change the signs of the edges in a complete network. These individuals are members of a social network who strategically reduce cognitive dissonances by changing their interpersonal appraisals. We characterize the best-response dynamics for this game and prove that its implementation can dynamically drive the network to a sociologically meaningful sign configuration called clustering balance. In this configuration, agents in the social network form one or more clusters that have positive relationships among their members but negative relationships among members of other clusters. In the past, various researchers in the fields of psycho-sociology, political science, and physics have looked at models that explain the generation of up to two clusters. Our work contributes to these fields by proposing a simple model that generates a broader class of signed networks.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

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

Journal: IEEE Transactions on Automatic Control

Publication Identifier Type:

Publication Identifier:

Volume:

Issue:

First Page #:

Date Submitted: 7/22/21 12:00AM

Date Published:

Publication Location:

Article Title: Polarization and Fluctuations in Signed Social Networks

Authors: Pedro Cisneros-Velarde, Kevin S. Chan, Francesco Bullo

Keywords: social networks, opinion dynamics, clustering balance

Abstract: Much recent research on social networks has focused on the modeling and analysis of how opinions evolve as a function of interpersonal relationships. It is also of great interest to model and understand the implications of friendly and antagonistic relationships. In this paper, we propose a new, simple and intuitive model that incorporates the socio-psychological phenomenon of the boomerang effect in opinion dynamics. We establish that, under certain conditions on the structure of the signed network that corresponds to the so-called structural balance property, the opinions in the network polarize. Compared to other models in the literature, our model displays a richer and perhaps more intuitive behavior of the opinions when the social network does not satisfy structural balance. In particular, we analyze signed networks in which the opinions show persistent fluctuations (including the case of the so-called clustering balance).

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Acknowledged Federal Support: Y

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

Journal: IEEE Transactions on Automatic Control

Publication Identifier Type: DOI

Publication Identifier: 10.1109/TAC.2021.3052485

Volume:

Issue:

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Date Submitted: 7/22/21 12:00AM

Date Published: 1/18/21 8:00AM

Publication Location:

Article Title: Social power evolution in influence networks with stubborn individuals

Authors: Ye Tian, Peng Jia, Anahita Mirtabatabaei, Long Wang, Noah E. Friedkin, Francesco Bullo

Keywords: Opinion dynamics, influence networks, social power, reflected appraisal, dynamical systems, mathematical sociology

Abstract: This paper studies the evolution of social power in influence networks with stubborn individuals. Based on the Friedkin-Johnsen opinion dynamics and the reflected appraisal mechanism, two models are proposed over issue sequences and over a single issue, respectively. These models generalize the original DeGroot-Friedkin (DF) model by including stubbornness. To the best of our knowledge, this paper is the first attempt to investigate the social power evolution of stubborn individuals basing on the reflected appraisal mechanism. Properties of equilibria and convergence are provided. We show that the models have same equilibrium social power and convergence property, where the equilibrium social power depends only upon interpersonal influence and individuals' stubbornness. Roughly speaking, more stubborn individual has more equilibrium social power. Moreover, unlike the DF model without stubbornness, we prove that for the models with stubbornness, autocracy can never be achieved....

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Acknowledged Federal Support: Y

RPPR Final Report as of 18-Jan-2023

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

Journal: Network Science

Publication Identifier Type: DOI

Publication Identifier: 10.1017/nws.2019.19

Volume: 7

Issue: 4

First Page #: 445

Date Submitted: 8/6/20 12:00AM

Date Published:

Publication Location:

Article Title: Positive Contagion and the Macrostructures of Generalized Balance

Authors: Noah E. Friedkin, Anton V. Proskurnikov, Francesco Bullo

Keywords: balance theory

Abstract: We propose a signed network formation game, in which pairs of individuals strategically change the signs of the edges in a complete network. These individuals are members of a social network who strategically reduce cognitive dissonances by changing their interpersonal appraisals. We characterize the best-response dynamics for this game and prove that its implementation can dynamically drive the network to a sociologically meaningful sign configuration called clustering balance. In this configuration, agents in the social network form one or more clusters that have positive relationships among their members but negative relationships among members of other clusters. In the past, various researchers in the fields of psycho-sociology, political science, and physics have looked at models that explain the generation of up to two clusters. Our work contributes to these fields by proposing a simple model that generates a broader class of signed networks.

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Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Scientific Reports

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41598-019-47759-4

Volume: 9

Issue: 1

First Page #: 12599

Date Submitted: 9/4/19 12:00AM

Date Published: 8/29/19 7:00AM

Publication Location:

Article Title: Collaboration in Complex Systems: Multilevel Network Analysis for Community-Based Obesity Prevention Interventions

Authors: Jaimie McGlashan, Kayla de la Haye, Peng Wang, Steven Allender

Keywords: obesity prevention, multi-level networks, Disease prevention, Public health, Risk factors

Abstract: Community-based systems interventions represent a promising, but complex approach to the prevention of childhood obesity. Existing studies suggest that the implementation of multiple actions by engaged community leaders (steering committees) is of critical importance to influence a complex system. This study explores two key components of systems interventions: (1) steering committees; and (2) causal loop diagrams (CLDs), used to map the complex community-level drivers of obesity. The interactions between two components create an entangled, complex process difficult to measure, and analysis of the dependencies between these two components in community-based systems interventions are limited. This study employs multilevel statistical models from social network analysis to explore the complex interdependencies between steering committee collaboration and their actions in the CLD. Steering committee members from two communities engaged in obesity prevention interventions reported

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RPPR Final Report as of 18-Jan-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 5-Submitted
Journal: Scientific Reports
Publication Identifier Type: **Publication Identifier:**
Volume: **Issue:** **First Page #:**
Date Submitted: 8/28/19 12:00AM **Date Published:**
Publication Location:

Article Title: Multiple Social Intelligence Domains Predict Group Social Networks

Authors: Kayla de la Haye, George G. Vega Yon, Jennifer Labrecque, Yeonjeong Kim, Thomas Malone

Keywords: social intelligence, emotional intelligence, Social Networks, Small Groups, teams, exponential random graph models

Abstract: Social network structures are shaped by individuals' personalities, but there has been limited research on the role of broader social abilities and traits. This study explores a range of individual social intelligence domains and their influence on the emergence of social networks among 42 newly formed groups of young adults working together in a laboratory setting. The mixed gender groups (3 to 5 members) completed a series of group tasks, followed by individual surveys measuring social intelligence, and perceptions of collaboration (advice, influence, trust), leadership, and antipathy networks in their group. Results of pooled exponential random graph models for small networks (ERGMito) found that socially perceptive individuals were more central in the collaboration and leadership networks, and that socially accommodating individuals trusted more members of their group and were less likely to be disliked. Overall, some social intelligence domains influence the emergence of small ...

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Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Social Networks
Publication Identifier Type: DOI **Publication Identifier:** 10.1016/j.socnet.2020.07.005
Volume: **Issue:** **First Page #:**
Date Submitted: 8/6/20 12:00AM **Date Published:**
Publication Location:

Article Title: Exponential Random Graph models for Little Networks

Authors: George G. Vega Yon, Andy Slaughter, Kayla de la Haye

Keywords: statistics, social networks, Exponential-Family Random Graph Models

Abstract: Statistical models for social networks have enabled researchers to study complex social phenomena that give rise to observed patterns of relationships among social actors and to gain a rich understanding of the interdependent nature of social ties and actors. Much of this research has focused on social networks within medium to large social groups. To date, these advances in statistical models for social networks, and in particular, of Exponential-Family Random Graph Models (ERGMS), have rarely been applied to the study of small networks, despite small network data in teams, families, and personal networks being common in many fields. In this paper, we revisit the estimation of ERGMs for small networks and propose using exhaustive enumeration when possible. We developed an R package that implements the estimation of pooled ERGMs for small networks using Maximum Likelihood Estimation (MLE), called "ergmito"....

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

Journal: Harvard Business Review

Publication Identifier Type:

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Volume: Issue:

First Page #:

Date Submitted: 9/5/19 12:00AM

Date Published: 2/25/19 5:38PM

Publication Location:

Article Title: Research: Men and Women Need Different Kinds of Networks to Succeed

Authors: Brian Uzzi

Keywords: social network, network centrality,

Abstract: To connect features of social networks at school to job placement success, we analyzed 4.5 million anonymized email correspondences among a subset of all 728 MBA graduates (74.5% men, 25.5% women) in the classes of 2006 and 2007 at a top U.S. business school. We measured job placement success by the level of authority and pay each graduate achieved after school.

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

Journal: Proceedings of the National Academy of Science

Publication Identifier Type: DOI

Publication Identifier: 10.1073/pnas.1901975116

Volume: 116 Issue: 43

First Page #: 21463

Date Submitted: 8/6/20 12:00AM

Date Published:

Publication Location:

Article Title: Quantifying the Future Lethality of Terror Organizations

Authors: Yang Yang, Adam R. Pah, Brian Uzzi

Keywords: Terrorism, Counter-terrorism, Human Conflict, Organizational Behavior, Statistical Models

Abstract: We propose a signed network formation game, in which pairs of individuals strategically change the signs of the edges in a complete network. These individuals are members of a social network who strategically reduce cognitive dissonances by changing their interpersonal appraisals. We characterize the best-response dynamics for this game and prove that its implementation can dynamically drive the network to a sociologically meaningful sign configuration called clustering balance. In this configuration, agents in the social network form one or more clusters that have positive relationships among their members but negative relationships among members of other clusters. In the past, various researchers in the fields of psycho-sociology, political science, and physics have looked at models that explain the generation of up to two clusters. Our work contributes to these fields by proposing a simple model that generates a broader class of signed networks.

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

Journal: Proceedings of the National Academy of Sciences

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Publication Identifier: 10.1073/pnas.1915516117

Volume: 117

Issue: 25

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Date Submitted: 8/6/20 12:00AM

Date Published: 6/1/20 7:00AM

Publication Location:

Article Title: Mentorship and protege success in STEM fields

Authors: Yifang Ma, Satyam Mukherjee, Brian Uzzi

Keywords: mentors, coarsened exact matching, science of science, career success, computational social science

Abstract: Einstein believed that mentors are especially influential in a protégé's intellectual development, yet the link between mentorship and protégé success remains a mystery. We marshaled genealogical data on nearly 40,000 scientists who published 1,167,518 papers in biomedicine, chemistry, math, or physics between 1960 and 2017 to investigate the relationship between mentorship and protégé achievement. In our data, we find groupings of mentors with similar records and reputations who attracted protégés of similar talents and expected levels of professional success. However, each grouping has an exception: One mentor has an additional hidden capability that can be mentored to their protégés. They display skill in creating and communicating prizewinning research. Because the mentor's ability for creating and communicating celebrated research existed before the prize's conferment, protégés of future prizewinning mentors can be uniquely exposed to mentorship for conducting celebrated....

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Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Management Science

Publication Identifier Type:

Publication Identifier:

Volume: 2020

Issue: 1

First Page #: 18198

Date Submitted: 7/22/21 12:00AM

Date Published:

Publication Location:

Article Title: Biased information transmission in investor social networks: Evidence from professional traders

Authors: Jacqueline Ng Lane, Sonya S. Lim, Brian Uzzi

Keywords: information transmission, social networks, management

Abstract: Theoretical studies postulate that information transmission in investor social networks has important implications for diverse market phenomena, including trading volume, price informativeness, liquidity, volatility, and trading strategies. Yet, we have limited knowledge about the real-world links among information exchange, trading decisions, and performance in investor social networks. Using more than 1 million instant message communications and more than 2 million trading records of professional traders, we directly measure how information propagates through traders' strong and weak network ties and its effects on their trading decisions and performance. Our results suggest that investment information sharing is asymmetric: traders are more likely to exchange information on trading gains over losses, especially with their strong ties. However, message receivers are more likely to trade on information from strong ties when the information

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

Journal: Academy of Management Proceedings

Publication Identifier Type: DOI

Publication Identifier: 10.5465/AMBPP.2019.19059abstract

Volume: 2019

Issue: 1

First Page #: 19059

Date Submitted: 7/22/21 12:00AM

Date Published: 8/1/19 9:00PM

Publication Location:

Article Title: Emotional Competence and Post-Crisis Behavior within Organizations

Authors: Kartikeya Bajpai, Brian Uzzi

Keywords: emotional competence, crisis management

Abstract: In the aftermath of a crisis, organizational actors face environments of high uncertainty which challenge rational models of decision making. As a consequence, emotional processes can meaningfully shape social interactions in crisis contexts. In this study, I adopt an interactionist perspective to theorize and test how interaction-generated affective impressions guide social action in the post-crisis period. Following cultural-normative organizational scholarship, I suggest that interactions within organizations are structured by norms relating to the display of emotions. Consequently, interactions utilizing appropriate emotional displays generate emotional uplift, and inappropriate emotional displays cause negative affect. I theorize that over the course of repeated interactions, such interpersonal emotional exchanges can lead to the formation of affective impressions of interaction partners....

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Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 5-Submitted

Journal: Proceedings of the National Academy of Science

Publication Identifier Type:

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Volume:

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Date Submitted: 8/18/20 12:00AM

Date Published:

Publication Location:

Article Title: Media Attention's Causal Effect on a Terror Group's Lethal Behavior

Authors: Yang Yang, Tian Yuan, Adam Pah, and Brian Uzz

Keywords: Terror group, media coverage

Abstract: Terror organizations are proliferating and growing in lethality worldwide. To combat the proliferation of terror organizations calls for insights from organizational research. Drawing on the insight from organization and strategy research that emphasizes the effect of information intermediaries on organizational outcomes, we study whether media attention to terrorist attacks has inadvertently fueled the growth of terrorist organizations in the past few decades. We collect novel data on media attention to terrorist organizations, and employ an instrumental variable approach stemming from the coincidence of natural disasters with attacks which generates exogenous variation in the amount of media attention to terrorist attacks. We find that terrorist groups whose past attacks garner more media attention are significantly more active, ceteris paribus, than groups that experience concurrent disasters that diverted media attention away....

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

Journal: Nature Physics

Publication Identifier Type:

Publication Identifier: 10.1038/s42005-020-00478-z

Volume: Issue:

First Page #:

Date Submitted: 7/22/21 12:00AM

Date Published:

Publication Location:

Article Title: The 1995-2018 Global Evolution of the Network of Amicable and Hostile Relations Among Nation-States

Authors: Omid Askarisichani, Ambuj K. Singh, Francesco Bullo, Noah E. Friedkin

Keywords: international news, balance theory, quantitative sociology, convex optimization, time-varying markov, data mining, international conflicts

Abstract: We draw on the data collected by the Integrated Crisis Early Warning System on millions of international and regional public news stories, and this system's indicators of the orientation toward a specific nation-state. We construct the networks of international amicable and hostile relations among nation-states that occur in specific time-periods in order to study the global evolution of the network of such international appraisals. Our analysis presents evidence of an evolution of the structure of this network and a model of the probabilistic micro-dynamics of the alterations of international appraisals during the 1995-2018 span of the available data. Our research provides empirical findings on long-standing debates in the interdisciplinary field of work on Structural Balance Theory. Also remarkably, we find that the trajectory of the Frobenius norm of sequential transition probabilities, which govern the evolution of international appraisals among nations, dramatically stabilizes.

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Journal: IEEE Transactions on Automatic Control

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Volume: Issue:

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Date Submitted: 7/18/22 12:00AM

Date Published: 3/7/22 8:00AM

Publication Location:

Article Title: Assign and Appraise: Achieving Optimal Performance in Collaborative Teams

Authors: Elizabeth Y. Huang, Dario Paccagnan, Wenjun Mei, and F. Bullo

Keywords: networks, transactive memory systems, coevolutionary networks, evolutionary games

Abstract: Tackling complex team problems requires understanding each team member's skills in order to devise a task assignment maximizing the team performance. This paper proposes a novel quantitative model describing the decentralized process by which individuals in a team learn who has what abilities, while concurrently assigning tasks to each of the team members. In the model, the appraisal network represents team member's evaluations of one another and each team member chooses their own workload. The appraisals and workload assignment change simultaneously: each member builds their own local appraisal of neighboring members based on the performance exhibited on previous tasks, while the workload is redistributed based on the current appraisal estimates. We show that the appraisal states can be reduced to a lower dimension due to the presence of conserved quantities associated to the cycles of the appraisal network. ...

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

Journal: Social Networks

Publication Identifier Type:

Publication Identifier: 10.1016/j.socnet.2020.12.009

Volume:

Issue:

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Date Submitted: 7/22/21 12:00AM

Date Published:

Publication Location:

Article Title: Group dynamics on multidimensional attitudes

Authors: Noah E. Friedkin, Anton V. Proskurnikov, Francesco Bullo

Keywords: Small groups, influence systems, multidimensional attitudes

Abstract: The literature on attitudes toward objects includes seminal research indicating that individuals locate an object in a multidimensional appraisal space defined by the object's perceived degree of being good or bad, weak or strong, and passive or active. We advance this research in three ways. First, we generalize the information integration on an object with the inclusion of other individuals' displayed attitudes toward the object, and posit the existence of a dynamical system of information integration that generates a network of interpersonal influences on group members' object appraisals. Second, we show that this influence system entails a set of non-obvious and rarely violated constraints on individuals' settled appraisals. Third, with data collected in experiments on groups' appraisals of images of nine animals and two nations, Russia and North Korea, we report empirical findings that support the existence of this system and its predicted constraints on individuals' object ...

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

Journal: Science Translational Medicine

Publication Identifier Type:

Publication Identifier: 10.1186/s12915-020-00868-3

Volume: 18

Issue: 1

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Date Submitted: 7/22/21 12:00AM

Date Published:

Publication Location:

Article Title: Importance of Scientific Collaboration in Contemporary Drug Discovery and Development: A Detailed Network Analysis

Authors: Feixiong Cheng, Yifang Ma, Brian Uzzi, and Joseph Loscalzo

Keywords: network analysis, drug development, decision making

Abstract: A growing evidence shows that scientific collaboration plays crucial role in transforming the life-science innovation. However, public understanding of how collaboration structures between academia and industry catalyze novel target identification and first- in-class drug discovery is limited. We perform a comprehensive institution network analysis on a large scientific corpus of collaboration and citations (0.17 billion of publications) to quantify the success trajectory of innovative drug development. By focusing on four types of cardiovascular drugs, we demonstrate the intangible collaboration structures among geographical institutions, the importance of network structures in drug discovery and development and the critical role of both academic institutions and pharmaceutical industries. We further show the knowledge flow network between institutions to highlight the underlying contributions of different institutions in the development of a new drug....

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 5-Submitted

Journal: Journal of the British Royal Society

Publication Identifier Type: Publication Identifier:

Volume: Issue: First Page #:

Date Submitted: 8/18/20 12:00AM Date Published: 1/1/01 8:00AM

Publication Location:

Article Title: Predicting Success in Multiteam Systems Based on Between Team Player Transfers

Authors: Satyam Mukherjee, Hongin Yun, Noshir Contractor, Brian Uzzi

Keywords: Team performance, Rivalry between past allies, Ecosystem hypothesis, Indian Premier League

Abstract: The small but growing body of research on the team vs. team competition focuses on multilevel factors including team's strength or prior relations among team members within a team, which influence relative performance of teams. A fundamental contribution of our research is demonstrating the significance and power of ecosystem factor in the outcome of a contest. Ecosystem is defined as a collection of members who belong to overlapping teams. Using data over a 5-year period in the Indian Premier League, we explore the effects of the ecosystem factor on team assembly in interactive contests. In the context of the Indian Premier League, ecosystem refers to the situation where former teammates compete against each other when playing for their franchise- owned teams. Having this 'prior knowledge' gives insight that one would not be facing a team of total strangers. Our results indicate that for Cricket matches played between 2012 and 2016 in the Indian Premier League (IPL), ...

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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Publication Type: Journal Article Peer Reviewed: **Publication Status:** 5-Submitted

Journal: Nature Human Behavior

Publication Identifier Type: Publication Identifier:

Volume: Issue: First Page #:

Date Submitted: Date Published:

Publication Location:

Article Title: New Methods for studying the Dynamics of Scientific Teams

Authors: B. Liu, B. Jones, Brian Uzzi, D. Wang

Keywords:

Abstract:

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

Journal: PLOS One

Publication Identifier Type: DOI Publication Identifier: 10.1371/journal.pone.0255990

Volume: Issue: First Page #:

Date Submitted: 3/28/22 12:00AM Date Published:

Publication Location:

Article Title: A Network Formation Game for the Emergence of Hierarchies

Authors: Pedro Cisneros-Velarde, Francesco Bullo

Keywords: network formation game

Abstract: We propose a novel network formation game that explains the emergence of various hierarchical structures in groups where self-interested or utility-maximizing individuals decide to establish or severe relationships of authority or collaboration among themselves. We consider two settings: we first consider individuals who do not seek the other party's consent when establishing a relationship and then individuals who do. For both settings, we formally relate the emerged hierarchical structures with the novel inclusion of well-motivated hierarchy promoting terms in the individuals' utility functions. We first analyze the game via a static analysis and characterize all the hierarchical structures that can be formed as its solutions. We then consider the game played dynamically under stochastic interactions among individuals implementing better-response dynamics and analyze the nature of the converged networks.

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Journal: IEEE Transactions on Automatic Control

Publication Identifier Type: Publication Identifier:

Volume: Issue: First Page #:

Date Submitted: 7/22/21 12:00AM Date Published:

Publication Location:

Article Title: Structural Balance via Gradient Flows over Signed Graphs

Authors: Pedro Cisneros-Velarde, Noah E. Friedkin, Anton V. Proskurnikov, Francesco Bullo

Keywords: balance theory, interpersonal influence

Abstract: Structural balance is a classic property of signed graphs satisfying Heider's seminal axioms. Mathematical sociologists have studied balance theory since its inception in the 1940s. Recent research has focused on the development of dynamic models explaining the emergence of structural balance. In this paper, we introduce a novel class of parsimonious dynamic models for structural balance based on an interpersonal influence process. Our proposed models are gradient flows of an energy function, called the dissonance function, which captures the cognitive dissonance arising from the violations of Heider's axioms. Thus, we build a new connection with the literature on energy landscape minimization. This gradient-flow characterization allows us to study the transient and asymptotic behaviors of our model. We provide mathematical and numerical results describing the critical points of the dissonance function.

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

Journal: Social Networks

Publication Identifier Type: Publication Identifier: 10.1016/j.socnet.2020.12.009

Volume: 65 Issue: First Page #:

Date Submitted: 7/22/21 12:00AM Date Published: 5/22/21 10:29PM

Publication Location:

Article Title: Group dynamics on multidimensional object threat appraisals

Authors: Noah E. Friedkin, Anton V. Proskurnikov, Francesco Bullo

Keywords: Small groups, Influence systems, Multidimensional threat appraisals

Abstract: The literature on attitudes toward objects includes seminal research on threat appraisals indicating that individuals locate an object in a multidimensional threat appraisal space defined by the object's perceived degree of being good or bad, weak or strong, and passive or active. We advance this research in three ways. First, we generalize the information integration on an object with the inclusion of other individuals' displayed appraisals, and posit the existence of a dynamical system of information integration that generates a network of interpersonal influences on group members' object appraisals. Second, we show that this influence system entails a set of non-obvious and rarely violated constraints on individuals' settled appraisals. Third, with data collected in experiments on groups' appraisals of images of nine animals and two nations, Russia and North Korea, we report empirical findings that support the existence of this system and its predicted constraints

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Sociological Science
Publication Identifier Type: DOI **Publication Identifier:** 10.15195/v7.a20
Volume: 7 **Issue:** **First Page #:** 487
Date Submitted: **Date Published:**
Publication Location:

Article Title: Generalized Markovian Quantity Distribution Systems: Social Science Applications

Authors: Noah Friedkin, Anton Proskurnikov

Keywords:

Abstract: The literature on attitudes toward objects includes seminal research on threat appraisals indicating that individuals locate an object in a multidimensional threat appraisal space defined by the object's perceived degree of being good or bad, weak or strong, and passive or active. We advance this research in three ways. First, we generalize the information integration on an object with the inclusion of other individuals' displayed appraisals, and posit the existence of a dynamical system of information integration that generates a network of interpersonal influences on group members' object appraisals. Second, we show that this influence system entails a set of non-obvious and rarely violated constraints on individuals' settled appraisals. Third, with data collected in experiments on groups' appraisals of images of nine animals and two nations, Russia and North Korea, we report empirical findings that support the existence of this system and its predicted constraints

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Acknowledged Federal Support: N

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Proceedings of the National Academy of Sciences
Publication Identifier Type: DOI **Publication Identifier:** 10.1073/pnas.2005737118
Volume: 118 **Issue:** 21 **First Page #:**
Date Submitted: 7/22/21 12:00AM **Date Published:** 5/1/21 7:00AM
Publication Location:

Article Title: Quantifying collective intelligence in human groups

Authors: Christoph Riedl, Young Ji Kim, Pranav Gupta, Thomas W. Malone, Anita Williams Woolley

Keywords: collective intelligence, human groups, team performance

Abstract: Collective intelligence (CI) is critical to solving many scientific, business, and other problems, but groups often fail to achieve it. Here, we analyze data on group performance from 22 studies, including 5,279 individuals in 1,356 groups. Our results support the conclusion that a robust CI factor characterizes a group's ability to work together across a diverse set of tasks. We further show that CI is predicted by the proportion of women in the group, mediated by average social perceptiveness of group members, and that it predicts performance on various out-of-sample criterion tasks. We also find that, overall, group collaboration process is more important in predicting CI than the skill of individual members.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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RPPR Final Report as of 18-Jan-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 5-Submitted

Journal: Organization Science

Publication Identifier Type:

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Volume: Issue:

First Page #:

Date Submitted: 7/22/21 12:00AM

Date Published:

Publication Location:

Article Title: A Theory of Coordination and Control Processes in the Multilayer Influence Networks of Complex Organizations
Organization Science

Authors: Noah E Friedkin, Anton V Proskurnikov

Keywords: complex organizations, social networks, group formations, interpersonal influence systems

Abstract: The coordination and control of activities in large-scale task-oriented organizations is a hard problem lying at the crossroads of network science and management science. The pursuit of a better understanding of such organizations is motivated by the limitations of the assumption that top-down transmissions of orders coupled with bottom-up transmissions of information on the scalar chains of an organization's authority structure are the necessary and sufficient conditions of coordination and control. In this article, we develop a multilayer theory of coordination and control, in which each layer is a dynamical system of interpersonal influences among agents who are oriented to a particular set of issues. We show how this approach enriches an understanding of the mechanistic foundations of control loss on scalar chains of authority and the inner workings of deliberative groups assembled to address problems of coordination or other issues requiring attention.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

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

Journal: Annals of the New York Academy of Sciences

Publication Identifier Type: DOI

Publication Identifier: 10.1111/nyas.14783

Volume: Issue:

First Page #:

Date Submitted: 7/18/22 12:00AM

Date Published:

Publication Location:

Article Title: Predictive Models for Human-AI Nexus in Group Decision-Making

Authors: Ambuj Singh, Francesco Bullo, Noah Friedkin, Omid Askarisichani

Keywords: decision making, human-AI teams, machine learning

Abstract: Machine Learning (ML) and Artificial Intelligence (AI) have had a profound impact on our lives. Domains like health and learning naturally require or are helped by human-AI interactions and decision-making. In these areas, as ML algorithms prove their value in making important decisions, humans add their distinctive expertise and judgment on social and interpersonal issues that need to be considered in tandem with algorithmic inputs of information. Some questions naturally arise. What rules and regulations should be invoked on the employment of AI, and what protocols should be in place to evaluate available AI resources? What are the forms of effective communication and coordination with AI that best promote effective human-AI teamwork? In this review, we highlight factors that we believe are especially important in assembling and managing the human-AI group decision-making.

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Authors: Thomas W. Malone
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CONFERENCE PAPERS:

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Conference Name: 25th International World Wide Web Conference	
Date Received: 17-Aug-2016	Conference Date: 11-Apr-2016
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Conference Name: 20th ACM Conference on Computer-Supported Cooperative Work and Social Computing (CSCW 2017)
 Date Received: 30-Aug-2017 Conference Date: 26-Feb-2017 Date Published: 26-Feb-2017
 Conference Location: Portland, OR
Paper Title: Deep structures of collaboration: Physiological correlates of collective intelligence and group satisfaction
Authors: P. Chikersal, M. Tomprou, Y. J. Kim, A. W. Woolley, L. Dabbish
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 Conference Location: Portland, OR
Paper Title: What makes a strong team? Using collective intelligence to predict team performance in League of Legends
Authors: D. Engel, Y. J. Kim, A. W. Woolley, J. Lin, N. McArthur, T. W. Malone
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Conference Name: 2016 IEEE 55th Conference on Decision and Control (CDC)
 Date Received: 30-Aug-2017 Conference Date: 12-Dec-2016 Date Published:
 Conference Location: Las Vegas, NV, USA
Paper Title: Dynamic models of appraisal networks explaining collective learning
Authors: Wenjun Mei, Noah E. Friedkin, Kyle Lewis, Francesco Bullo
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Paper Title: Putting the Pieces Back Together Again: Contest Webs for Large-Scale Problem Solving
Authors: Thomas W. Malone, Jeffrey V. Nickerson, Robert J. Laubacher, Laur Hesse Fisher, Patrick de Boer, Yu
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Conference Name: 2017 IEEE 33rd International Conference on Data Engineering (ICDE)
Date Received: 31-Aug-2017 Conference Date: 19-Apr-2017 Date Published:
Conference Location: San Diego, CA, USA
Paper Title: A Distance Measure for the Analysis of Polar Opinion Dynamics in Social Networks
Authors: Victor Amelkin, Petko Bogdanov, Ambuj Singh
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Conference Name: Download book PDF EPUB International Conference on Complex Networks and their Applications
Date Received: 29-Aug-2018 Conference Date: 30-Nov-2017 Date Published: 28-Nov-2017
Conference Location: Lyon, France
Paper Title: Modeling the Co-evolution of Committee Formation and Awareness Networks in Organizations
Authors: Alex T. Jones, Noah E. Friedkin, Ambuj K. Singh
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Paper Title: Optimizing network structure for preventative health
Authors: Bryan Wilder, Han Ching Ou, Kayla de la Haye, Milind Tambe
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Conference Name: ACM Conference
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Paper Title: Scholar Plot: Designing a Well-Abstracted and Scalable Interface for Academic Performance
Authors: Dinesh Majeti, Brian Uzzi, Ergun Akleman, Ioannis Pavlidis, Alexander Petersen
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Conference Name: IEEE Big Data
Date Received: 27-Aug-2019 Conference Date: 11-Dec-2018 Date Published:
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Paper Title: Learning Multiclassifiers with Predictive Features Varied along with Data Distribution
Authors: Xuan Hong Dang, Omid Askarisichani, Ambuj K. Singh
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Conference Name: the 25th ACM SIGKDD International Conference
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Paper Title: Fighting Opinion Control in Social Networks via Link Recommendation
Authors: Victor Amelkin, Ambuj K. Singh
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Conference Name: The 31st Canadian Conference in Computational Geometry (CCCG)
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Conference Location: Edmonton, Canada
Paper Title: On Multi-Dimensional Team Formation
Authors: Thomas Schibler, Ambuj Singh, Subhash Suri
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Paper Title: Feature Learning for Event Detection on Dynamic Graphs
Authors: Mert Kosan, Arlei Silva, Sourav Medya, Brian Uzzi, Ambuj Singh
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Authors: Nada Hashmi

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Authors: Erik Duhaime

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Authors: Shadi Mohagheghi

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Title: Essays on Bioinformatics and Social Network Analysis: Statistical and Computational Methods for Complex Systems

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Institution: University of California, Santa Barbara

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Title: Networks of Coupled Oscillators and Social Network Structures of Teams

Authors: Elizabeth Huang

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Institution: University of California, Santa Barbara

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Title: Explainable Models of Performance on Networks

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Authors: Pedro Cisneros

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Partners

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I certify that the information in the report is complete and accurate:

Signature: Ambuj K. Singh

Signature Date: 3/28/22 6:12PM

Network Science of Teams MURI

ARO Grant# W911NF-15-1-0577

Final Report, 2015-2021

PI: Ambuj Singh, University of California, Santa Barbara
Co-PIs: Francesco Bullo, University of California, Santa Barbara
Kayla de la Haye, University of Southern California
Noah Friedkin, University of California, Santa Barbara
Thomas Malone, Massachusetts Institute of Technology
Brian Uzzi, Northwestern University

Project Overview

The recent convergence of research in social and psychological sciences, dynamic and quantitative modeling, and network science has led to a re-examination of collective team behavior from a quantitative and systems-oriented viewpoint. Teams cannot be understood fully by studying their components (members) in isolation: team performance is not simply a sum of individual performances; and a diversity of opinions among members leads to better group outcomes. However, it is not yet understood how patterns of interactions and relationships among team members (i.e. team networks) impact performance. Understanding these patterns is critical, as the resolution of complex issues requires deliberative within-group interaction processes in which alternative courses of action are surfaced, evaluated, and acted upon.

Accomplishments

From 2015-2021 our project made efforts to

- Enable leaders to identify a broader set of strategies for creating successful teams, based on the characteristics of individual members, network structures, and emergent groups;
- Identify processes that enable the emergence of optimal interaction patterns for a given set of individuals or teams, and improve team performance over task sequences;
- Reveal scalable team structures to develop theories and tools for the decomposition of complex tasks;
- Apply machine learning and optimization to identify new approaches that teams and organizations can use to adapt to new and unfamiliar environments.

We maintained steady progress against each of our proposed milestones, organized as four research threads. An overview of our effort follows with highlights sorted by thread, task, and sub-task (Thread#.Task#.Subtask#).

Thread 1: Teams as networks of interacting entities.

(Lead: Singh)

We viewed teams as semantically-labeled, multilevel networks with attributes on nodes, edges, and subgroups. In this thread, we developed models of team performance: both statistical models using networks and fine-grain models of information flows. We then examined the relationship between influence networks and collective intelligence on task performance, as we considered the robustness and optimization of teams.

1.1 Conceptual models for teams and tasks

(de la Haye, Friedkin, Malone)

1.1.1: Refine the conceptual model of team performance, including properties of the “team space” and “task space”

In Year 1, the team successfully developed detailed working conceptual models of “team space” and “task space”, which informed the direction of future research across this and other Thrusts and Tasks. De la Haye’s lab, in collaboration with PI Malone’s lab, developed protocols to test how various “social system smarts” constructs, such as social intelligence and holistic thinking, and network structure (and the disruption of these social dynamics) explain team collective intelligence. Uzzi’s work produced novel insights about the critical role of communication network structure, and communication complexity, in decision sequences in large organizations.

Our second year efforts identified domains of the team space relevant to performance. We found that social abilities are multifaceted, but that some domains can have a negative impact on team performance.

In years three through five, we continued to develop and refine models conceptualizing team performance, including properties of the “team space” and “task space”, building on collected data. This refinement continued to contribute to subsequent milestones.

1.1.2: Develop multilevel models of team performance, identifying individual, network, and group-level predictors using experimental and observational data

Models of team performance identified both team member and team social network predictors, as well as direct and indirect influence paths on performance. In 2017, we found that group-level social intelligence aggregates directly predicted team Collective Intelligence (CI). We also identified indirect paths in multilevel models, whereby team social abilities predicted the formation of various types of emergent social networks, which in turn predicted team CI performance.

We continued to study multi-team systems in 2018 and 2019. We examined how the transfer of team members across teams that are in competition with one another is related to cross team information flow and competitive success. We also examined how an external threat changes interteam information flows within an organization made up of many small teams.

1.1.3: Identify the role of “social system smarts” in team performance and strategies for training individuals in this skill

Participants in our 2017 study individually completed a large battery of social ability measures, including eight measures of personality, social, and emotional intelligence. A factor analysis revealed three discrete social intelligence factors based on the personality and emotional/social intelligence measures. These factors were found to be independent of social perceptiveness abilities.

In 2018, we found that social abilities predict team collective intelligence directly, and through their influence on team social networks. We conducted analyses to identify dimensions of “social system smarts”, including team cognitive social structures; these results were presented at a conference in 2018 and a manuscript is in preparation. Finally, we completed a literature review of training curricula to improve learned social abilities in adult populations.

In 2019 we continued work linking team social abilities, social networks, and performance. In a submission to Network Science, we showed that social intelligence predicts performance directly, and via its influence on the formation of team social networks. A second paper utilized new developments in exponential random graph models for small networks to test how multiple domains of teammates’ social intelligence predicts the formation of multifaceted social networks of influence, trust, advice-seeking, leadership, and antipathies in teams.

1.2 Statistical and content-based models

(Singh, de la Haye)

1.2.1: Develop suite of methods for extracting subnetworks that discriminate between teams with varying performance metrics

In 2016, Singh and Malone explored how team collaboration patterns affected performance. For teams that communicated via text chats, they used the text logs to create a collaboration network representation for teams. They then used the network-level features to explain team performance as well as to categorize tasks. Results show that more frequent and uniformly spread collaboration positively affects team performance. Also, there is a consistent task taxonomy obtained based on either how team members collaborate or how well the teams perform.

Also in 2016, Abdelzaher undertook the challenge of discovering the characteristics of individuals and networks that correlate with superior performance on information-centric tasks. Results of his research offer insight into ways to account for social ties in such source selection problems to maximize performance on information-centric tasks.

In 2017, we began an empirical study on the link between team performance and the patterns of intra-team collaboration to study collective performance in collaboration networks. Well-connectedness of collaboration networks, measured via algebraic connectivity, is linked to

higher team performance. The designed predictive models showed high accuracy---a relative error of 15-25%---on a variety of simple tasks, outperforming baseline models. We used online multiplayer games for data-driven team performance prediction with smoothness imposed on SVM classifiers. Our results showed that, in experienced teams, team-features are far more important than individual skills. Plus, team uniformity and standard deviation of team proficiency are important.

In 2017, de la Haye and collaborators completed multilevel analyses on team-level decision making and performance, and identified individual, network, and group-level predictors of team performance using experimental and observational data.

1.2.2 Develop models of team performance and a characterization of their accuracy on empirical datasets

In 2018, we completed a manuscript on understanding the features responsible for performance of teams on interactive gaming tasks. We demonstrated the performance of our proposed model on two important application domains of network science and sociology, and compared it against other multi-task learning algorithms. The empirical results showed that our model not only achieves higher prediction accuracy but its discovered patterns also reflect variations in data distribution.

In 2019, collaboration with Slaughter at ARL, we made major advances in the application of exponential random graph models (ERGM or p models) for small team networks. We submitted a paper on this work and developed the “ergmito” package for R (and associated packages “gnet” and “similR”) that was shared with CRAN.

In 2020, we finalized and disseminated work on new extensions for exponential random graph models for small networks, including the “ergmito” package for R. This work included simulations and the application of the ergmito models to empirical data collected in Years 1-3.

1.2.3: Develop a method for analyzing transactive memory based on information flows

In 2018, we used Balance Theory to examine how social relationships (“friends” vs.” enemies”) share information important to transactive memory systems (TMS). We later published a paper on social networks under stress in the ACM Transactions on the Web. We had a related paper in the Review of Economics and Statistics on what we have titled “the Reverse Matthew Effect” relating to scientific teams.

Work on the robustness of team responses to threats using the day trader dataset from prior years led to a paper submission and to presentations at AFE/AEA meetings and the Academy of Management. We submitted a paper to the 2021 ACM International Conf. on Web Search and Data Mining. The paper introduced graph neural network architectures that capture structural, temporal, and attribute information and learn their relationship with labeled events.

1.2.4: Extend the developed method from earlier milestones to other measurements of cognitive state of teams

In 2020, our work on Balance Theory to understand how the quality of sentiments among team members influences individual and team performance resulted in a Nature Communications publication exploring risky decision making. We also published an article in PNAS about the lethality of terror organizations; and we submitted a follow-up article to PNAS

that builds on those results. Finally, our longitudinal data on hedge funds led to two presentations at the Academy of Management. The first of these guides managers in the discovery of the mechanisms allowing them to map information sharing in their companies. The second presentation explores emotional competence of team members following a crisis.

1.3 Group performance and influence networks

(Friedkin, Bullo, Malone)

1.3.1: Advance the measurement models of Collective Intelligence with the construct of combinatorial collective intelligence

Early on, we established an experiment that secured the usefulness of the Friedkin-Johnsen model of opinion dynamics in advancing research on the collective-intelligence group-performance linkage. The experiment collected data on 161 individuals nested in 30 groups, each dealing with a sequence of 8 tasks. In the first two years of the MURI project, we continued to study the role played by influence systems in the efficient functioning of teams, as for example when tackling judgmental, intellectual or resource allocation tasks. This work led to a Scientific Reports paper on mathematical structures in group decision-making. Our subsequent work proposed a theoretical model of how a team performs accurate estimation tasks and how the wisdom of crowd phenomenon arises and is affected by social influence. Remarkably, we showed various fragility results in large populations arising whenever the expertise of individuals is latent.

1.3.2: Group performance along a task sequence

Results from our human subject experiments on group decision making for resource allocation problems set up a very rich inquiry into how groups deal with adaptations across an issue sequence.

1.3.3: Further advance the existing research on the collective intelligence

In 2018, we completed and published a study of group performance and influence networks on intellectual tasks. We conducted new experiments on the mathematical architecture of group decision-making, and published a paper on the results. We published another paper on the relationship of balance theory and group performance. We conducted experiments on group threat appraisal responses and on prospect theory responses to choice dilemma problems. We successfully ran additional experiments on choice dilemmas at Fort Bragg.

In 2019, we continued work investigating the level of a team's performance based on the individual skills of team members and the relationships among team members. We published results in *Nature Human Behaviour*. Our work on mind+machine intelligence partnerships, focusing on how machines can become teammates and contacts in a network, resulted in six conference presentations and, ultimately, a publication in *PNAS*.

1.4 Robustness and task assignment

(Bullo, Singh)

1.4.1: Elaborate on ideas of robustness and resiliency in the framework of teams and tasks

We embarked on a study of approaches that improve social cohesion, such as minimizing team complexity, and their resulting optimal social/team structures. We studied the impact of these and other social/team structures on bias propagation and information reliability. Finally, we explored the relation between social/team structures on failure propagation in larger organizations.

In 2018, we elaborated on ideas of robustness and resilience in the framework of teams and tasks by examining the predictive power of several theoretical models, including Markov Chain, spectrum analysis, random walks in modular networks, and basic SI, SIR models.

1.4.2: Develop a solution to the team assignment problem using these accomplishments of milestone 1.4.1.

In 2019, we developed a solution to the team assignment problem using accomplishments of earlier milestones.

Thread 2: Analysis and models of dynamic team behavior

(Lead: Bullo)

In our second research thread, we examined the performance of teams on a sequence of tasks. Our first sub-task examined the changes in social influence networks resulting from repeated tasks. The second sub-task explored team adaptivity using methods from computational learning and data-driven optimization.

2.1 Interpersonal influences on task sequences and evolving networks

(Friedkin, Bullo, de la Haye, Uzzi)

2.1.1: Undertake a study of the collective intelligence-performance linkage among a task sequence

At the start of our MURI, we conducted experiments involving random permutations of eight tasks considered in sequence by groups. The findings indicate important task-sequence effects on a collective intelligence that is expressed in group performance. These effects include social learning along the sequence, which has strong ties with the 2.2.1 milestone on learning and optimizing dynamic team behavior.

We proposed a general non-linear model of polar opinion dynamics that allows individuals' susceptibility to persuasion to be a function of their current opinions. We studied three specializations having different socio-psychological interpretations and provided a comprehensive theoretical analysis.

In 2018, we completed the work on influence systems along sequences of intellectual issues, for which group performance is measured by whether the group succeeds in forming consensus on a correct position or not.

We completed work on the multidimensional opinion dynamic problems subject to logical constraints. The constraints on the beliefs affect collective convergence to a shared belief system. The quantitative model explains how an idiosyncratic set of arbitrarily linked beliefs held by a few may become held by many. We studied the design of a model governing the process of polar opinion formation in a group, capturing non-linear traits of the opinion formation process.

To explore Balance Theory in a network, we used a financial trading firm dataset and compared the structure of interpersonal relations among financial traders. We found that the system tends to transition from imbalanced to balanced over time, meaning that traders are actively reconfiguring the structure of their social ties within their communication networks to reduce sentiment violations. Moreover, we find a positive association between a trader's degree of structural balance and their trading performance.

In 2019 we completed a manuscript on the empirical analysis of balance theory on trader networks. This article reports findings from the most extensive set of longitudinal data yet assembled to evaluate the theory's prediction of an evolution toward structural balance.

In 2020, our paper on social intelligence predicting collective intelligence showed that change in team performance over a series of tasks is predicted by the composition of the teams' social abilities. Teams whose members had diverse "social gregariousness" characteristics were more likely to improve their performance over the series of tasks.

2.1.2: Develop a study of the collective intelligence-performance linkage among a task sequence and the comparison of the linkage along task sequences composed of intellectual (full information) and non-intellectual (withheld information) problems.

This subtask advances work on group-level intellectual tasks with known individual-level task biases, and the same tasks converted to a non-intellectual form with critical information withheld. Our 2018 paper in PNAS on collective intelligence-performance along task sequences, as well as highlights from 1.3.3 above, describe our advances against this milestone subtask.

2.1.3: Advance the existing research on the collective intelligence performance linkage with comparisons of influence network adaptations in a comparison of task sequences composed of intellectual and non-intellectual tasks.

As described in 2.1.1, we published work on the dynamical evolution to appraisal systems towards equilibrium appraisals consistent with balance theory and based on influence and homophily methods. We also published a paper on dynamics that propagate true positions on intellectual problems, and a paper on temporal changes related to the evolution of appraisal networks.

In 2019 we continued work on the links between TMS and biased information flow within teams. We published a related paper on the flow of information in a network and performance in PNAS. This paper investigates gender composition in a network.

Our experiments on an intellectual memory task found that task performance and higher values of self-appraisal are the two most salient factors in determining the amount of influence a group member may receive.

In 2019, we also continued working on Group Prospect Theory and analyzing the data collected from UCSB and Fort Bragg. We formulated a novel distance measure between individuals (or groups) using the learned prospect theory parameters. Our investigation of the hedge fund dataset suggested the performance of traders is tied to the stability of sentiment, the size of traders' social networks, and the proportion of different types of messages. Our paper on multidimensional threat appraisals of encountered objects examined the implicit micro dynamic rules that operate in the interpersonal influence systems of groups evaluating an object. We published a paper on interpersonal appraisal networks that solves the generalized balance theory problem of the evolution to balanced networks.

In 2020, we published a paper that applies balance theory to data on the evolution of the global network of international appraisals among nations.

2.2 Learning and optimizing dynamic team behavior

(Bullo, Friedkin, Malone, Singh)

2.2.1: Learning and optimization along task sequences

Bullo and Friedkin proposed a novel series of quantitative models on "Team Learning and Performance via Assign/Appraise Dynamics." They considered three baseline models with increasing complexity, starting from a centralized manager-based assignment and learning model, and finishing with a social model of interpersonal appraisal, assignments, learning, and influences. They show how rational optimal behavior arises along the task sequence and discuss conditions of sub-optimality. Developed models are grounded in replicator dynamics from evolutionary games, influence networks from mathematical sociology, and transactive memory systems from organization science.

PIs also explored a project considering multi-armed bandits in the context of repeated assignment of tasks to teams, assuming a latent structured space that encodes the attributes of individuals, teams, and tasks.

In 2017, we completed the work on dynamic models of appraisal networks explaining collective learning. In a paper proposing models of learning process in teams of individuals who collectively execute a sequence of tasks, we showed how rational optimal behavior arises along the task sequence for each model, and discussed conditions of suboptimality. Our models are grounded in replicator dynamics from evolutionary games, influence networks from mathematical sociology, and transactive memory systems from organization science.

We developed novel theoretical extensions of the DeGroot-Friedkin (DF) model for the dynamical evolution of individuals' self-appraisal and social power in a social influence network. First, we proposed novel models and analysis results for noisy DF models over stochastically-changing influence networks. Second, we considered a model modification, in which the opinion formation process takes place on the same timescale as the reflected appraisal process.

We also provided a practical solution to online team-task assignment, where the task is unknown and skill representations of team members are known. Using a geometric interpretation of team collaboration and task success probability, we extended results from multi-armed bandit (MAB) algorithms to achieve provably-high success rates in repeatedly

assigning teams to a fixed, unknown tasks. Our main technical contribution in this area was a Thompson Sampling upper bound which exploits similarities between arms to show instance-dependent asymptotic regret which can be sublinear in the number of arms.

2.2.2: Develop strategies for more general control signals, e.g., manipulating micro-interactions and the interpersonal influence network tailored to intellectual and non-intellectual tasks. Learning for dynamic teams along task sequences.

We continued to investigate collective learning phenomena connected with TMS and influence systems, focusing on various mechanisms for performance feedback information and for the dynamics of appraisal networks. We presented a paper at KDD paper on fighting opinion control via link recommendation.

In 2020 we completed work on modeling collective learning phenomena in groups along task sequences. We provided rigorous results characterizing the ability (or inability) of team members to learn each other's skill and thus converge to an allocation maximizing the team performance.

In related research, we examined the phenomenon of control loss on chains-of-command, and the network conditions that mitigate control loss. We show that lateral (gangplank) arcs of influence mitigate control loss, and how decentralized deliberative groups operate to reduce problems of coordination.

Finally, in 2020, we completed our analysis of instant messages exchanged among employees, wherein we model the dynamics of the communication network and relate messages to team performance. Results showed that we can find which behaviors lead to high performance and can predict the roles of employees based on their behaviors.

2.2.3: Develop algorithms for dynamic teams based on models developed for teams in which individual characteristics and network interactions have a dynamics of their own.

In our third year of the MURI, building from our earlier work on dynamic models for collective learning in appraisal networks and their relationship with TMS, we made progress towards the analysis of stochastic models and more general classes of tasks and performance functions. We also made substantial progress and submitted two research manuscripts and a survey chapter on the mathematical modeling and dynamical system analysis of the evolution of social power in influence systems via the reflected appraisal mechanism. Novel results included an understanding of single timescale models and of the influence of noise and memory in social power dynamics.

In 2019 we published a conference paper on the topic of team formation. We considered a team formation problem in multi-dimensional space where the goal is to group a set of n agents into t teams, each of size b , to maximize their total performance. We developed an efficient algorithm for solving the problem in two dimensions, as well as an algorithm for computing a single optimal team in any constant dimension.

In 2020 we investigated the problem of learning features for event detection directly from data, which enables the design of domain-agnostic event detection systems. Our results show that learned features outperform competing approaches in many settings while requiring a small amount of training data and computational resources.

Thread 3: Network science of teams of teams

(Lead: Malone)

In our third thrust, we broke new ground in team design by scaling teams to solve complex tasks (i.e. teams of teams), and advancing social science theories of team performance. Given a complex task, this thrust considered how to decompose it into subtasks, the effect of inter-task dependencies, and how to assign teams to such tasks. We considered the learning of optimal decomposition and coordination structures using methods from reinforcement learning, and we examined adaptivity over nested tasks and learning of optimal coordination structures.

3.1 Structure and assignment for nested tasks

(Malone, de la Haye, Uzzi)

3.1.1: Analyzing micro-level interaction patterns in groups

Much of the research on the network science of teams of teams began with PI Malone at MIT. Early in our project, his lab conducted preliminary micro-level analyses of group interactions focusing on how group members actually perform task assignment and coordination activities. He sought to identify a generalized coordination process of teamwork that leads a group to perform intelligently. Data for this study were obtained from previous research on collective intelligence (CI).

In 2017, we conducted preliminary micro-level analyses of group interactions focusing on how group members actually perform task assignment and coordination activities. Our goal was to identify a generalized coordination process of teamwork that leads a group to perform intelligently. We published the results in 2018 in *Network Science*.

Also in 2018, we undertook analyses of the micro-level social interaction and communication data, based on the audio and video capture of real-time team performance in the USC laboratory study. We conducted a meta-analysis of team performance and conducted norming/scaling procedures using the large-size team dataset cumulated over the past years. Furthering our milestone, in 2019 we analyzed four data sets to identify various factors influencing the levels of consensus of human judgments. Depending on evaluation stimuli and dimension, different numbers of raters are needed to achieve reliable group evaluations. Computer algorithms can help allocate different numbers of raters for different targets and evaluation dimensions.

Also, we conducted a series of experiments on prospect theory at Fort Bragg and UCSB. Preliminary analysis of these data presented some remarkable findings on individual and group effects of risky decision making.

We established a new lab for Group Social Dynamics at USC with additional support from a ARO-funded DURIP award. The lab boasts a state-of-the-art group behavioral observation system that uses audio and video recordings, and behavioral coding systems, to measure individual and group behaviors and “micro-behaviors” in real time.

Finally, in 2020, we continued our investigation into distributed evaluations to identify various factors influencing the levels of consensus of human judgments. We found the extent to which inter-rater reliability can be enhanced by increasing the number of judges. We also investigated how computers can help groups make more reliable and efficient evaluations.

3.1.2: Incentives for self-assignment to tasks

One of our early experiments toward this milestone involved a creative group task at MIT: writing a short love story about two characters, Sam and Rhea. In this experiment, over 120 groups of between 10 and 30 workers were recruited on Amazon Mechanical Turk and asked to contribute to a part of the story. At the end of the experiment, each integrated story was evaluated and those who contributed to the top-ranked story split a prize in various ways, varying both the incentive structure and the relative importance of each subtask. Additional manipulations varied the workload and pay-off of tasks, providing additional data for consideration. The experiment continued into 2017 and 2018. To broaden the scope and robustness of this work, we ran similar experiments where workers created a 3 day travel itinerary.

In additional studies involving this milestone, we found that six judges were enough to reliably estimate targets' moral character, and that the average of judges' moral character evaluations predicted targets' unethical behaviors. We also published a manuscript on models and comparative analysis of four multi-group connectivity structures: co-memberships, edge bundles, bridges, and liaison hierarchies.

3.1.3: Skill combinations for assignment to tasks

In another group study, we examined how doctors diagnose breast cancer in mammography images. Through collecting a large dataset on how multiple individuals and machine intelligence systems diagnose the same test set of mammography images, we determined which combinations of diagnoses and which decision rules lead to a higher accuracy. An iPhone/iPad application that displays mammographic images to users was developed. We made available an iPhone/iPad application that displays mammographic images on the App Store. Results suggested that the combination of people and computers together was more accurate than either alone. In 2019, using a new biopsy dataset dataset, we expanded the research to develop a manuscript on how to most effectively combine human and artificial intelligence for diagnosing skin cancer. Here we explored the conditions under which human-computer groups outperform artificial intelligence alone at diagnosing skin cancer. Portions of the project led to the creation of a company with a PhD student funded by the MURI as founder and CEO.

In 2018, we investigated how CI may work in organizations by examining two communication patterns: Relay Rate of similar trading information across teams and between team diversity/concentration. We also focused on a new analysis of team interactions: the communication dynamics among employees with different titles and roles.

In 2019, through field studies, we analyzed multilevel team-task network data from two community coalitions (teams) who were taking actions on a set of interdependent community projects (tasks) to reduce children's health risks. We found that the structure of the coalition

collaboration network predicted actions on tasks in the second-level task network. We published our results in Scientific Reports.

Finally, we published an article in May 2020 suggesting how combining human and artificial intelligence can raise confidence in research. A second article in June 2020 explores mentorship and protege success in STEM fields. A third paper uses a network analysis to demonstrate the importance of scientific collaboration in contemporary drug discovery and development.

3.1.4. Coordinating dependencies among tasks: Group decision-making for investment management

The day trader data set and analysis referenced above in earlier milestones was particularly relevant to milestone 3.1.4. Using this data, we investigated how collective intelligence (CI) may work in organizations. Specifically, we examined two communication patterns: Relay Rate of similar trading information across teams and between team diversity/concentration. We found that increased relay and less diversity were both human network responses to uncertainty. This was because personnel on different teams circulated information faster, and to more diverse teams, to reduce risk and to coordinate the overall firm portfolio of investments.

Task 3.2 Composite models for nested tasks

(Bullo, Friedkin, Singh)

3.2.1: Develop theories for optimizing the decomposition of teams and tasks and evaluate the methods experimentally.

After a comprehensive literature review on the four prototypical control and organization structures discussed in the proposal for this project, we focused on the development of generative models for the four cases, and their comparative analysis. Our generative models relied upon models from random-graph theory, but were grounded in Sociology literature.

In a related 2017 experiment, we proposed a maximum coverage model for optimal construction of a committee for non-routine tasks. While deliberating, group communication and actions alter an organization's memory network by establishing face- to-face interactions and bridging distinct communities. We established a simple network augmentation model to capture these dynamics and an efficient algorithm to select committees.

In 2018 we studied the problem of forming multiple teams from a network of individuals such that each team has a coverage of requisite skills, uniformity of risk-taking, uniformity of network connectivity, and at the same a diversity of risk-taking. We developed an algorithm and conducted experiments on synthetic data. We then published papers on the implication of different connectivity structures that link multiple teams and on how different connectivity structures affect control loss on hierarchical chains of authority administering multiple task-oriented teams.

In 2019 we made considerable progress on the development of a model of the coordination and control of large-scale complex organizations. We continued to investigate multi-group connectivity structures in organizations, including their connectivity modalities, the

implications for various performance metrics, and their strategic game-theoretic modeling in handling control and coordination problems. Work led to a paper on multi-group connectivity structures.

We have also made progress on understanding a separate group formation mechanism related to balance theory. This work resulted in a publication in *Dynamic Games and Applications*. Also related to group formation mechanisms, we have solved several open problems in the theory of the evolution of appraisal networks toward structural balance; this work appeared in *Network Science* in 2019.

In an ongoing work, we are developing a general model of group behavior dynamics utilizing Cumulative Prospect Theory and the Friedkin-Johnsen Opinion dynamics model, which we call Group Prospect Theory (GPT). Our results suggest the importance of a network science perspective in understanding the complex process of individual and group behavior evolution within social groups.

Our paper titled, “Assign and Appraise: Achieving Optimal Performance in Collaborative Teams” was accepted to *IEEE Transactions on Automatic Control* and will appear in 2022.

Abstract: This paper proposes a novel quantitative model describing the decentralized process by which individuals in a team learn who has what abilities, while concurrently assigning tasks to each of the team members. In the model, the appraisal network represents team member’s evaluations of one another and each team member chooses their own workload. The appraisals and workload assignment change simultaneously: each member builds their own local appraisal of neighboring members based on the performance exhibited on previous tasks, while the workload is redistributed based on the current appraisal estimates. We show that the appraisal states can be reduced to a lower dimension due to the presence of conserved quantities associated to the cycles of the appraisal network. Building on this, we provide rigorous results characterizing the ability, or inability, of the team to learn each other’s skill and thus converge to an allocation maximizing the team performance. We complement our analysis with extensive numerical experiments.

Thread 4: Research into Human-agent Teams

(Lead: Singh)

The perfect team of the future will most likely consist of humans and AI agents. To this purpose, we conducted experiments to explore and optimize teams of humans with computer assistance.

4.1 A platform for investigating human-agent teams

(Singh, Malone)

4.1.1 Develop an online platform for experimenting with groups and tasks under controlled settings, for research in Human-agent teams.

We continued to maintain and improve The Platform for Online Group Students (POGS 2.0) with user testing and bug fixing, and we worked to make the software accessible to the broader community.

In 2020 we began development and testing of another tool to support ad hoc, private conversations that often occur before, after, or during the breaks of face-to-face human meetings, but that are difficult to achieve in commonly used video conferencing systems. This platform could benefit ad hoc, private videoconferences for group problem-solving.

4.1.2 Experiments on human-agent team optimization

From 2018-2020 we conducted multiple experiments with human subjects to explore how they integrate their individual decisions into a group response, how much they rely on agents in their team, and how an agent's input affects their decision making process. Results contributed to multiple theses and publications.

We proposed models investigating the dataset with multiple approaches employing Bayes rule, eigenvector centrality of human influence and expected agent performance, along with Prospect Theory applied to the aforementioned algorithms.

4.2 A methodology for designing human-agent groups

(Singh, Friedkin, Malone)

4.2.1 A methodology for designing human-computer groups.

Building on the frameworks in the SUPERMINDS book, we are developing a systematic methodology that can be used to design innovative forms of human-computer groups.

Our paper on Predictive Models for Human-AI Nexus in Group Decision-Making was accepted to the *Annals of the New York Academy of Sciences* for publication in 2022.

Abstract: Machine Learning (ML) and Artificial Intelligence (AI) have had a profound impact on our lives. Domains like health and learning naturally require or are helped by human-AI interactions and decision-making. In these areas, as ML algorithms prove their value in making important decisions, humans add their distinctive expertise and judgment on social and interpersonal issues that need to be considered in tandem with algorithmic inputs of information. Some questions naturally arise. What rules and regulations should be invoked on the employment of AI, and what protocols should be in place to evaluate available AI resources? What are the forms of effective communication and coordination with AI that best promote effective human-AI teamwork? In this review, we highlight factors that we believe are especially important in assembling and managing the human-AI group decision-making.

4.2.2 Creating super-intelligent human-computer groups.

By systematically searching for combinations of tasks and human-computer group configurations that produce order-of-magnitude performance improvements beyond today's state-of-the-art, we expect to develop scientifically based guidelines for how to do machine-assisted cognition in a wide range of situations.

4.2.3 Human-AI Decision Making on Truth Statements.

In 2020 we conducted experiments to explore how human-AI teams reach a decision on intellectual tasks under heterogeneous expertise levels and limited information. Our findings suggest that the proposed models are able to explain decision making in teams.

Presentations

MURI participants disseminated results through publications and presentations. We listed a total of 152 presentations throughout our interim reports from 2015-2021. All publications (journal articles, conference presentations, books, etc) are included in the Products section.

1. Abdelzاهر, Tarek. (2015, November). "Cyber-Physical Systems in Social Spaces," Invited Tutorial, EMSIG Autumn School, Copenhagen, Denmark.
2. Abdelzاهر, Tarek. (2015, December). "Social Network Data Distillation Services for Urban Spaces," Keynote Talk, Middleware, Vancouver, Canada.
3. Uzzi, Brian. (2016). Computational Methods and Networks. Cultures Enterprises Conference, Edinburgh, Scotland.
4. Uzzi, Brian. (2016, January). Chronometric Theory and Knowledge Production. NetSciX, Poland.
5. Abdelzاهر, Tarek. (2016, January). "Social Sensing in Urban Spaces," Keynote Talk, 17th International Conference for Distributed Computing and Networking (ICDCN), Singapore.
6. Shao, Huajie, Tarek Abdelzاهر. (2016, April). "Who To Ask? Analysis of Information Robustness," XXXVI Sunbelt Conference of the International Network for Social Network Analysis, Newport Beach, CA.
7. Amelkin, Victor, Omid Askarisichani, Young Ji Kim, Ambuj Singh, Thomas Malone. (2016, April). "Dynamics of Collective Performance in Collaboration Networks," XXXVI Sunbelt Conference of the International Network for Social Network Analysis, Newport Beach, CA.
8. Friedkin, Noah E., Peng Jia and Francesco Bullo. (2016, April) "A Formal Theory of The Evolution of Social Power: Natural Trajectories of Interpersonal Influence Systems Along Issue Sequences" XXXVI Sunbelt Conference of the International Network for Social Network Analysis, Newport Beach, CA.
9. de la Haye, K., Labrecque, J. (2016, April). Integrating theories of health behavior, social networks, and systems science. XXXVI Sunbelt Conference of the International Network for Social Network Analysis, Newport Beach, CA.
10. Liess, Matthias, Christian Schultz, Dirk Helbing, and Brian Uzzi. (2016, April). Overcoming Decision Biases through Network Structure. XXXVI Sunbelt Conference of the International Network for Social Network Analysis, Newport Beach, CA.
11. Uzzi, Brian. Diversity and Networks (2016, April). Rochester University Conference on Diversity. New York.
12. Horvat, Eموke-Agnes, Jay Uparna, Brian Uzzi. (2016, June). Unraveling Crowd IQ Signals in Crowdfunding. Collective Intelligence Conference, New York.
13. Liess, Matthias, Christian Schultz, Dirk Helbing, and Brian Uzzi. (2016, June). Social Networks and Stochastic Decision Making. Collective Intelligence Conference, New York.
14. Uzzi, Brian. (2016, June). Knowledge Search and Breakthrough Ideas: Teams and Networks International Conference on Computational Social Science, Evanston, IL.
15. Romero, Daniel, Brian Uzzi and Jon Kleinberg. (2016, June). Social Networks Under Stress. International Conference on Computational Social Science, Evanston, IL.
16. Whalen, Ryan, Satyam Mukherjee and Brian Uzzi. (2016, June). Legal Decision Evolution: Temporal Patterns of Precedent Citation & Judicial Opinion Impact. International Conference on Computational Social Science. Evanston, IL.

17. Casasnovas, Julia Poncela-, Tarek Abdelzaher, Brian Uzzi. (2016, June). Error Propagation in Networks: the case of the New York City Garment Industry Supply Chain. International Conference on Computational Social Science. Evanston, IL.
18. Kim, Y. J., & Aggarwal, I. & Woolley, A. W. (2016, June). How communication impacts team performance: Exploring collective intelligence and transactive memory system as mechanisms. Paper presented at the 2016 Annual Convention of the International Communication Association. Fukuoka, Japan. (Top Paper Award; Organizational Communication Division)
19. Kim, Y. J., Aggarwal, I. & Woolley, A. W. (2016, June). How collective intelligence impacts team performance: Exploring transactive memory system as a mechanism. Paper presented at the 2016 Collective Intelligence Conference. New York.
20. Micheli, Rita Maria, Daniel Romero, and Brian Uzzi. (2016, July). Topic diffusion and network structure in complex organizations: The example of hedge funds. EGOS, Naples, Italy.
21. Kim, Y. J. & Woolley, A. W. (2016, July). The effect of team extraversion on coordination and collective intelligence. Paper presented at the 2016 INGRoup Conference. Helsinki, Finland.
22. Engel, D., Kim, Y. J. Woolley, A. W., Lin, J., McArthur, N., & Malone, T. W. (2016, July). What makes a strong team? Collective intelligence predicts team performance in League of Legends. Paper presented at the 2016 INGRoup Conference. Helsinki, Finland.
23. Glikson, E., Harush, R., Kim, Y. J., Woolley, A. W., & Erez, M. (2016, July). Psychological safety and collective intelligence in multicultural globally distributed teams. Paper presented at the 2016 INGRoup Conference. Helsinki, Finland.
24. Engel, D., Kim, Y. J. Woolley, A. W., Lin, J., McArthur, N., & Malone, T. W. (2016, August). What makes a strong team? Collective intelligence predicts team performance in League of Legends. Paper presented at the Annual Meeting of the Academy of Management. Anaheim, CA.
25. Singh, Ambuj. (2016, August). "Detecting Significant Network Processes." Indian Institute of Science, Bangalore, India.
26. Singh, Ambuj. (2016, August). "Detecting Significant Network Processes." International Conference on Complex Acute Illness, Pasadena.
27. Engel, D., Kim, Y. J., Woolley, A. W., Lin, J., McArthur, N., & Malone, T. W. (2016, August). "What makes a strong team? Using collective intelligence to predict performance of teams in League of Legends." Paper presented at the 2016 Annual Meeting of the Academy of Management, Anaheim, CA
28. Friedkin, Noah. (2016, November). "Truth Propagation." Invited talk at Insead, Singapore.
29. Singh, Ambuj. (2016, December). "Outlier Detection from Network Data with Subnetwork Interpretation." International Conference on Data Mining, Barcelona, Spain.
30. de la Haye, K., & Labrecque, J. S. (2017, January). "Social network dynamics: Bridging individual and collective social factors in group performance." Paper presented at the Social Psychology in the 21st Century: New Methods, Statistical Tools, and Crossing Disciplinary Boundaries Preconference of the 18th annual meeting of the Society of Personality and Social Psychology, San Antonio, TX.
31. Labrecque, J. S., & de la Haye, K. (2017, January). "Social system smarts explain collective intelligence in teams." Poster presented at the 18th annual meeting of the Society of Personality and Social Psychology, San Antonio, TX.
32. Yifang Ma, Julia Poncela-Casasnovas, Brian Uzzi. (2017, January). "Evolutionary Patterns in Interorganizational Networks: Growth, Contraction, and Substitution." International School and Conference on Network Science (NetSci-X Winter).
33. Kim, Y. J., Aggarwal, I., & Woolley, A. W. (2017, February). "How collective intelligence impacts team performance: Exploring transactive memory system as a mechanism." Poster presented at the Organizational Science Winter Conference, Park City, UT.
34. Singh, Ambuj. (2017, March). "Advancing Wisdom of Networks." ANN/SONIC Workshop.
35. Labrecque, J. S., & de la Haye, K. (2017, March). "Social system smarts explain collective intelligence in teams." Poster presented at the 8th International Workshop on Network Theory: Wisdom in Networks, Los Angeles, CA.
36. Singh, Ambuj. (2017, April). "GPOP: Group-level Popularity Prediction for Online Content." World Wide Web Conference, Perth, Australia.
37. Singh, Ambuj. (2017, April). "Detecting Significant Network Processes." University of New South Wales, Sydney.

38. de la Haye, K, Labrecque, J, Kim, YJ, Malone, T (2017, May). "Social networks and social intelligence explain collective intelligence in groups." Paper presented at the XXXVII Sunbelt Conference of the International Network for Social Network Analysis, Beijing, China.
39. Duhaime, E.P. (2017, May). "The Wisdom of Organized Crowds." Presentation at the East Coast Doctoral Conference at Columbia University, New York, NY.
40. Woolley, A. W., Riedl, C., Kim, Y. J., & Malone, T. W. (2017, June). "More evidence for a general collective intelligence factor in human groups: A meta-analysis." Paper presented at the 2017 Collective Intelligence Conference, New York City, NY.
41. Malone, T. W., Nickerson, J. V., Laubacher, R. J., Fisher, L. H., de Boer, P., Han, Y., Towne, W. B. (2017, June). "Using contest webs to address the problem of global climate change." Paper presented at the 2017 Collective Intelligence Conference, New York City, NY.
42. Engel, D., Malone, T. W. (2017, June). "Integrated information as a metric for group interaction: Analyzing human and computer groups using a technique developed to measure consciousness." Paper presented at the 2017 Collective Intelligence Conference, New York City, NY.
43. Mukherjee, Satyam, Noshir Contractor, and Brian Uzzi. (2017, June). "Ecosystem factor influencing the victor in team vs. team competitions." Science of Team Science Conference.
44. Chikersal, P., Tomprou, M., Kim, Y. J., Woolley, A. W., & Dabbish, L. (2017, July). "Physiological and behavioral synchrony predicts collective intelligence and group satisfaction." Paper presented at the 2017 INGRoup Conference, St Louis, MO.
45. de la Haye, K, Labrecque, J, Kim, YJ, Malone, T (2017, July). "Social smarts shape social networks." Paper presented at the North American Social Networks (NASN) Conference, Washington, D.C., USA.
46. Labrecque, J, de la Haye, Kim, YJ, Malone, T (2017, July). "Network structure explains the relationship between social abilities and team performance." Paper presented at the North American Social Networks (NASN) Conference, Washington, D.C., USA.
47. Bullo, F. (2017, July). On the Dynamics of Influence and Appraisal Networks. Plenary at 14th SIAM Conference on Control and its Applications, Pittsburgh, PA, USA.
48. de la Haye, K. (2017, August). Social network interventions for health promotion. Invited talk at University of Southern California Center for Artificial Intelligence in Society, Los Angeles, USA.
49. Micheli, M.R., Romero, D., and Uzzi, B. (2017, August). Topic diffusion and intra-organizational interaction: the case of hedge funds. Presentation at the Academy of Management Annual Meeting. Atlanta, Georgia, USA.
50. Singh, A. (2017, August). Network Science of Teams. Presentation to the Office of the Secretary of Defense, Washington DC, USA.
51. Singh, A. (2017, August). Discovering Network Processes in Multilayer Time-evolving Networks under Incomplete Information. Presentation at NS-CTA PI meeting, Newark, Delaware, USA.
52. Horvat, E., Uparna, J., and Uzzi, B. (2017, September). Hidden Indicators of Collective Intelligence in Crowdfunding. Presentation at Social Informatics. Oxford, UK.
53. Malone, T. W. (2017, September). The Impact of Technology and Innovation on the Future of Work. Plenary panel at Eisenhower Fellowships Future of Work Global Conference. Malaga, Spain.
54. Malone, T. W. (2017, September) Creating more intelligent organizations. MIT Sloan Alumni Online webinar.
55. Bullo, F. (2017, November). On the Dynamics of Influence and Appraisal Networks. Distinguished Lectures at the Electrical & Computer Engineering Department, University of Toronto. Toronto, Canada.
56. Malone, T. W. (2017, November). Mobilizing private finance towards sustainable infrastructure: Latin America's experience of NDC implementation. Panel at COP 23 (23rd annual "Conference of the Parties") UNFCCC (United Nations Framework Convention on Climate Change) (UN Climate Change Conference), Bonn, Germany.
57. Malone, T. W. (2017, November). How can we create more intelligent organizations? Presentation at Alliance ARTEM Conference (Ecole Nationale Supérieure d'Art et de Design de Nancy, ICN Business School, Mines Nancy, Université de Lorraine, Metropole GrandNancy), Nancy, France.
58. Malone, T. W. (2017, December). Bringing the digital revolution to the climate change challenge: The Climate Action Plan Accelerator. Presentation at Real Colegio Complutense at Harvard Workshop on "New Trends on Sustainability," Cambridge, MA, USA.
59. Malone, T. W. (2017, December). How can we create more intelligent organizations? Presentation at MIT Industrial Liaison Program Executive Session for MFS, Cambridge, MA, USA.

60. Malone, T. W. (2017, December). Collective Intelligence: What is it? How can we measure it? And how can we increase it? Workshop with MIT Center of Brain, Minds, and Machines and German Science of Intelligence Consortium, Cambridge, MA, USA.
61. Friedkin, N., Mei, W., Proskurnikov, AV., Bullo F. (2017, December). Automatic Polytopes in Group Decision Making on Resource Allocations. Presentation at the 2017 Conference on Decision and Control. Melbourne, Australia.
62. Singh, A.K. (2018, February). Detecting Significant Network Processes, Presentation at Workshop on Graph Techniques for Adversarial Activity Analytics, 11th ACM International Conference on Web Search and Data Mining. Los Angeles, CA, USA.
63. de la Haye, K. (2018, March). Using network science for health promotion & disease prevention. Invited talk at Brain Awareness Week, Azusa Pacific University, Azusa, CA, USA.
64. Malone, T. W. (2018, April). Superminds: The surprising power of people and computers thinking together. Presentation at MIT Industrial Liaison Program Information and Communication Technologies Conference, Cambridge, MA, USA.
65. Singh, A.K. (2018, May). Detecting Significant Network Processes. Presentation at Department of Computer Science, Arizona State University, Phoenix, AZ, USA.
66. Malone, T. W. (2018, May). Superminds: The surprising power of people and computers thinking together. MIT Book Launch Event, Cambridge, MA, USA.
67. Malone, T. W. (2018, May). Superminds: The surprising power of people and computers thinking together. Presentation at IE School of International Relations Course, Cambridge, MA, USA.
68. Malone, T. W. (2018, May). Superminds: The surprising power of people and computers thinking together. Presentation at MIT William Barton Rogers Society Reception, Los Angeles, CA, USA.
69. Malone, T. W. (2018, June). Superminds: The surprising power of people and computers thinking together. Presentation at Columbia University Age Boom Academy, New York, NY, USA.
70. Malone, T. W. (2018, June). Superminds: The surprising power of people and computers thinking together. Presentation at Society for Information Management Advanced Practices Council, Cambridge, MA, USA.
71. Malone, T. W. (2018, June). Superminds: The surprising power of people and computers thinking together. RamsayTalks, Toronto, Canada.
72. Uzzi, B. (2018, June). The Science of Science: Collaboration Strategies for Improving Scientific Impact. DRUID, Copenhagen, Denmark. (Keynote Address).
73. Poncela, J., Pah, A., Uzzi, B. (2018, June). Links between scientific success and team collaboration dynamics on online platforms. ICWSM, Palo Alto, CA, USA.
74. Wu, Y., Yang, Y., Uzzi, B. (2018, June). An Artificial and Human Intelligence Approach for the Replication Problem in Science. ICWSM, Palo Alto, CA, USA.
75. de la Haye, K., Labrecque, J., Kim, Y.J., Malone, T. W. (2018, June). Social smarts shape social networks and collective intelligence. Presentation at the XXXVIII Sunbelt Conference of the International Network for Social Network Analysis, Utrecht, the Netherlands.
76. Bullo, F. (2018, June). On the Dynamics of Influence and Appraisal Networks. Keynote at the 30th Chinese Control and Decision Conference, Shenyang, China.
77. Bullo, F. (2018, June). On the Dynamics of Influence and Appraisal Networks Workshop on Distributed Control and Multi-Agent Systems. Presentation at the Academy of Mathematics and Systems Science, Beijing, China.
78. Bullo, F. (2018, July). On the Dynamics of Influence and Appraisal Networks. Invited talk at Zhejiang University, Hangzhou, China.
79. Malone, T. W. (2018, July). Superminds: The surprising power of people and computers thinking together. Presentation at IESE International Symposium on Business Ethics, Barcelona Spain.
80. Malone, T. W. (2018, July). Superminds: The surprising power of people and computers thinking together. Presentation at Tortoise ThinkIn on "The Future of Listening," Boston, MA, USA.
81. Yang, Y, Pah, A., and Uzzi, B. (2019, July). Quantifying the future lethality of terror organizations. American Society of Criminology, San Francisco, CA, USA.
82. Malone, Thomas W. (2019, July). The human-computer superminds in our future. Plenary panel on "The future reimagined," International Risk Assessment and Horizon Scanning Symposium.
83. Jin, C., Ma, Y., and Uzzi, B. (2019, July). The Midas Touch: Quantifying the Impact of Awards on Scientific Developments, IC2S2, Amsterdam.

84. Vega Yon, G., de la Haye, K. (2019, July). Exact statistics and semiparametric tests for small network data. 5th International Conference on Computational Social Science (IC2S2), Amsterdam, Netherlands.
85. Vega Yon, G., de la Haye, K. (2019, June). Exact statistics and semi-parametric tests for small network data. 39th Sunbelt Conference of the International Network for Social Network Analysis (INSNA), Montreal, Canada.
86. de la Haye, K. (2019, June). Freeman Award Keynote Presentation, 39th Sunbelt Conference of the International Network for Social Network Analysis (INSNA), Montreal, Canada. [Invited presentation]
87. Malone, Thomas W. (2019, June). Superminds: The power of people and computers thinking together. MIT Technology Review EmTech Next Conference, Cambridge, MA.
88. Yang, Y, Pah, A., and Uzzi, B. (2019, June). A model for quantifying the future lethality of terror organizations. DRRC Intergroup Conflict & Cooperation Conference, Northwestern U., Chicago, IL, USA.
89. Liu, B., Wang, D., and Uzzi, B. (2019, May). Preferential Abandonment induces Structural Collapse in Robust Networks: Evidence from Scientific Fields and Technology Products. NetSci, Vermont, USA.
90. Malone, Thomas W. (2019, May). Superminds: The surprising power of people and computers thinking together. MIT / Junior Achievement Centennial Executive Forum on "Innovation and the Future of Work," Cambridge, MA.
91. de la Haye, K. (2019, May). Social intelligence and social networks predict group collective intelligence, Army Research Laboratory West, Playa Vista, USA. [Invited presentation]
92. Bullo, F. (2019, April). Network Systems. Distinguished Lecture, Colloquia Roberto Tempo on Automatica, Politecnico di Torino, Torino, Italy.
93. Malone, Thomas W. (2019, April). How can science and engineering help answer big questions about human and machine intelligence? (Panel Member), MIT Charter Society, Boston, MA.
94. Vega Yon, G. (2019, April). Big Problems for Small Networks: Statistical Analysis of Small Networks and Team Performance, The University of California, Irvine, CA, USA. [invited presentation]
95. Vega Yon, G. (2019, March). Big Problems for Small Networks: Statistical Analysis of Small Networks and Team Performance SONIC Lab Speaker Series, Northwestern University. Chicago, IL, USA. [invited presentation]
96. Malone, Thomas W. (2019, March). Superminds: The surprising power of people and computers thinking together. Network Sciences Institute, Northeastern University, Boston, MA.
97. Guszczka, J., Schwartz, J. (2019). Superminds: How humans and machines can work together (Interview with Thomas Malone), Deloitte Review.
98. Bullo, F. and Singh, A. (2019, January). Inferring Network Structure and Flows Using Partial Observations. Defense Threat Reduction Agency, Fairfax, VA, USA.
99. Singh, A. (2019, January). Machine Learning on Networks. Qatar Computing Research Institute, Qatar.
100. Malone T.W. (2019, January). How superminds can help us become the species we want to be. Presentation at Futures Congress, Punta Arenas, Chile.
101. Malone T.W. (2019, January). Superminds: The surprising power of people and computers thinking together. Presentation at the Chilean Institute of Rational Business Administration (ICARE) and at the Federation of Chilean Industry (SOFOFA), Santiago, Chile.
102. Vega Yon, G., de la Haye, K. (2019, January). Small network statistics for the network science of teams. NetSciX 2019, Santiago, Chile.
103. Vega Yon, G. (2018, December). Redes y Econometría Espacial con R. Pontificia Universidad Catolica de Chile, Santiago de Chile. Universidad del Desarrollo, Santiago de Chile. [invited presentation]
104. Malone, Thomas W. (2018, November). Superminds: The surprising power of people and computers thinking together, MIT Industrial Liaison Program Symposium on "Shaping the Future of Work,"
105. Madrid, Spain. Singh, A. (2018, November). Machine Learning on Networks. Computer Science Department, Indian Institute of Technology, Patna, India.
106. Duhaime, E. P. (2018, November) If You Can't Beat Them, Join Them: Collective Intelligence Outperforms Both Human and Artificial Intelligence at Diagnosing Skin Cancer. INFORMS Annual Meeting in Phoenix, AZ.
107. Malone, Thomas W. (2018, November). The genius of groups and computers thinking together, MIT Technology Review "Innovation Leaders Summit," Paris, France.
108. Malone, Thomas W. (2018, November). Superminds: The surprising power of people and computers thinking together, Eden McCallum breakfast and discussion event, London, UK.

109. Malone, Thomas W. (2018, October). Superminds: The surprising power of people and computers thinking together (Panel member in session on "Intelligent Designs"), Boston Book Festival, Boston, MA.
110. Uzzi, B. (2018, October). Topics in the science of science, AI, Replication, and Mentorship Effects. Duke University, NC, USA.
111. Uzzi, B. (2018, October). An Artificial and Human Intelligence Approach for the Replication Problem in Science. UT Austin, TX, USA.
112. Uzzi, B. (2018, October). Topics in the science of science, AI, Replication, and Mentorship Effects. Purdue University, IN, USA.
113. Bullo, F. (2018, October). Perspectives on the History, Sociology, and Mathematics of Influence Systems. Forum on Robotics & Control Engineering, University of South Florida, Tampa, FL, USA.
114. Wu, Youyou, Yang, Y, Uzzi, B. (2018, October). An Artificial and Human Intelligence Approach for the Replication Problem in Science. 9th International Ann-Sonic-NICO conference, Northwestern U., Chicago, IL, USA.
115. Bullo, F. (2018, September). Network Systems and Kuramoto Oscillators. Plenary, SICE Annual Conference, Nara, Japan.
116. Baipai, K., Uzzi, B, and Weber, K. (2018, September). Examining the Mediating Role of CulturalFit in the Aftermath of a Stigmatizing Organizational Event. Strategic Management Conference, Paris, France.
117. Malone, Thomas W. (2018, September). Moving toward the instinctive enterprise: Artificial intelligence, collective intelligence, and why they matter (Panel member), MIT Technology Review / Genpact Symposium, Cambridge, MA.
118. Malone, Thomas W. (2018, September). The future of work (keynote address). University of Zurich Digital Forum, Zurich, Switzerland.
119. Malone, Thomas W. (2018, September). Superminds: The surprising power of people and computers thinking together, Eden McCallum seminar, London, UK.
120. Yang Y., Chawla, N., Uzzi, B. (2018, August). Network Evolution: Exploring the Dynamics of Organizational Networks. Academy of Management Meetings, Chicago, IL, USA.
121. Wu, Y., Yang, Y., Uzzi, B. (2018, August). An Artificial and Human Intelligence Approach for the Replication Problem in Science. Am. Soc. Assoc. (Computational Soc Sci pre-meeting), Philadelphia, PA, USA.
122. Vega Yon, G., de la Haye, K. (2018, July). Big problems for small networks: Small network statistics. North American Social Network (NASN) Conference, Washington, D.C., USA.
123. Poncela, J., Pah, A., and Uzzi, B. (2018, May). Links between scientific success and team collaboration dynamics on online platforms. ICWSM, Palo Alto, CA, USA.
124. Wu, Y., Yang, Y, Uzzi, B. (2018, May). An Artificial and Human Intelligence Approach for the Replication Problem in Science. ICWSM, Palo Alto, CA, USA.
125. de la Haye, K. (2018, April). Developing independent academic research in an era of team and convergent science. Team Science Symposium, University of Southern California, Los Angeles, USA. [Invited panelist]
126. Malone, Thomas W. (2019, August). The human-computer superminds in our future. Aspen Institute Roundtable on Institutional Innovation, Aspen, CO.
127. Malone, Thomas W. (2019, August). Superminds: The surprising power of people and computers thinking together. Invited presentation on the "Science" stage for the Library of Congress National Book Festival, Washington, DC. See: <https://www.loc.gov/events/2019-national-book-festival/about-this-event/>.
128. Micheli, M. R., Romero, D., Giuseppe, I., and Uzzi, B. (2019, August). Topic diffusion and intra-organizational interaction: The case of hedge funds. Academy of Management Meetings, Boston, MA, 2019.
129. Baipai, K., Uzzi, B, and Weber, K. (2019, August). Emotional Competence and Post-Crisis Behavior within Organizations: An Analysis of a Hedge-Fund after a Regulatory Raid, Academy of Management, Boston, MA, USA.
130. Malone, Thomas W. (2019, September). Superminds: The power of people and computers thinking together. MIT Industrial Liaison Program Bristlecone Pulse Conference, Cambridge, MA.
131. Malone, Thomas W. (2019, September). Creating human-computer superminds. MIT Quest for Intelligence workshop on "Collective Intelligence," Cambridge, MA.
132. Malone, Thomas W. (2019, October). (Instigator) Panel discussion on "Markets," The Human Movement Kickoff workshop, Half Moon Bay, California.

133. Malone, Thomas W. (2019, October). Superminds: The Collective Intelligence of Community Bio. Global Community Bio Summit, Cambridge, MA.
134. Malone, Thomas W. (2019, October). Superminds: The power of people and computers thinking together. School for Advanced Research (SAR) Annual Public Creative Thought Forum Lecture (joint with Innovate Educate 2019 Close It Summit), Santa Fe, NM.
135. Malone, Thomas W. (2019, October). (Panel member). Better World (Atlanta), MIT Campaign for a Better World, Atlanta, GA.
136. Bullo, Francesco. (2019, November). Parsimonious Models for Opinion Dynamics and Structural Balance. Presentation at the Workshop on Network Dynamics in the Social, Economic, and Financial Sciences. Politecnico di Torino, Italy.
137. Malone, Thomas W. (2019, November). Human-Computer Collaboration. MIT Industrial Liaison Program W911NF1510577 : QUANTA: Quantitative Network-based Models of Adaptive Team Behavior 6 of 8
138. Malone, Thomas W. (2019, November). Human-Computer Collaboration. MIT Industrial Liaison Program 2019 Research and Development Conference on "Human and Technology Collaboration," Cambridge, MA.
139. Malone, Thomas W. (2019, November). (Interviewed by Gary Bolles) Superminds: The Power of Collaboration, Techonomy 2019 Conference, Half Moon Bay, CA.
140. Malone, Thomas W. (2019, November). Superminds (Dinner presentation in which Malone was interviewed by Yuri Milner), Breakthrough Prize Foundation laureates dinner, Los Altos Hills, CA.
141. de la Haye, K. (2019, December) Social intelligence and social networks impact the performance of small groups. ETH Zurich, Zurich, Switzerland.
142. Malone, Thomas W. (2019, December). Institutions as superminds: Five forms of group decision-making. (keynote presentation). Interdisciplinary conference on "The Choice II: Market, Organization, Democracy, Algorithm, or Community?" University of Michigan, Ann Arbor, MI.
143. Malone, Thomas W. (2020, March). Superminds: The surprising power of people and computers thinking together. US Deloitte Chief Learning Officer Forum, Virtual Workforce Innovation Forum 2020 (online).
144. de la Haye, K, Horn, A, Spruijt-Metz, D, Lee, B, French, S. (2020, April). Transdisciplinary innovations to assess and change local and global food systems to support healthy eating (symposium). Society for Behavioral Medicine Annual Meeting, San Francisco, USA.
145. Malone, Thomas W. (2020, May). COVID-19 and the Future of Work, MIT Industrial Liaison Program Webinar (online) (<https://ilp.mit.edu/attend/covid-19-and-future-work>).
146. Vega Yon, GG, Dinkjian, A, Hamm-Alvarez, S, de la Haye, K. (2020, June) ERGMito: Statistical models for small team social networks. International Science of Team Science Conference (Virtual).
147. Malone, Thomas W. (2020, June). COVID-19 and Collective Intelligence (invited plenary). ACM Collective Intelligence 2020 Conference (online) (<https://ci2020.weebly.com/program.html>).
148. Nada Hashmi, Thomas W. Malone. (2020, June). Effects on Collective Intelligence of Online Collaboration Tools and Group Size. ACM Collective Intelligence 2020 Conference (online) (<http://2020.conference.ci/>).
149. Yang, Yang, Youyou Wu, and Brian Uzzi. (2020, August). "Estimating the deep replicability of scientific findings using human and artificial intelligence." American Psychological Association Meetings, Chicago
150. Jacqueline Ng Lane, Sonya Lim, and Brian Uzzi. (2020, August). Biased information transmission in investor social networks: Evidence from professional traders. Annual Meeting of the Academy of Management (Virtual).
151. Malone, Thomas W. (2020, August). Minglr: Supporting ad hoc, private conversations online (invited plenary). Microsoft New Future of Work Symposium (online). (<https://www.microsoft.com/en-us/research/event/new-future-of-work/>).
152. Friedkin, Noah. (2020, September). Invited talk at a workshop on "Dynamics over Networks: Epidemics, Opinions and Information" organized as part of the newly established C3.ai Digital Transformation Institute.

Training

We received add-on funds from the Army Educational Opportunities Program (AEOP) to onboard two UC Santa Barbara (UCSB) undergraduate students and one Santa Barbara area high school student for an 8-week summer research experience (June - August 2021). Selected participants would become apprentices to the MURI researchers and join in program activities.

In collaboration with AEOP, MURI participants visited local nearby high school computer science classes and reached out to undergraduate advisors across UCSB. We distributed promotional fliers and fielded questions in an attempt to build interest.

Because of COVID and the remote nature of the program, UCSB undergraduate participation was low. In lieu of a second undergraduate intern, we obtained permission to recruit a second high school student. Our choice UCSB undergraduate accepted a competing internship offer.

Our two high school apprentices had only taken basic programming courses in Java. To bolster their skills, we paired them with participants in a data science boot camp made up of undergraduate students and funded by an NSF program. The boot camp was run by a graduate student in PI Singh's lab and the graduate student who assisted Co-PI Friedkin with the MURI human subjects protocol. Apprentices learned basics of Python programming and machine learning techniques, along with lessons on basic statistics and data visualization. Having formed a bond with the members of the boot camp, the AEOP participants continued for six more weeks with a team-based project in data exploration and analysis.

We encouraged apprentices to participate in weekly skills development classes and lectures hosted by UCSB's Center for Science and Education Partnerships (CSEP), as well as all programmatic activities put forth by AEOP.

Outside of the AEOP opportunity, our MURI's only other training activities involved graduate students in the course of their education and research.

Personnel

All personnel supported on this MURI have been added elsewhere in this report.

Tech Transfer

Fort Bragg

PIs de la Haye, Friedkin, and Singh traveled to Fort Bragg on July 30, 2018. They were joined by Edward Palazzolo and Adam Jonas. The goals of the visit were to transfer the MURI research to the 92nd Civilian Affairs Battalion and to conduct some teams of teams experiments. As it turns out, the Fort Bragg structure is ideal for "Teams of Teams" experiments. The 92nd Civilian Affairs Battalion has teams of four with 4-5 teams within a company and 5-6 such companies within the battalion. PIs used this visit to plan running some human subjects experiments on prospect theory.

Software

ergmito: The ergmito R package implements methods for estimating and analyzing exponential random graph models for small networks using exact statistics. Among the package's functionalities, we have: estimation of pooled models, exact log-likelihood and its gradient, vectorized functions for calculating sufficient statistics on large sets of small networks, simulation of ERGMs using exact statistics, etc. The R package is already available on the MURI GitHub website (<https://github.com/muriteams/ergmito>) and will be shipped to CRAN in August 2019.

Authors: George G. Vega Yon, Kayla de la Haye

gnet: An experimental R package built on top of ergmito that implements a Monte Carlo test for association between graph level outcomes and network-based statistics such as those used in ERGMs. This is work in progress but can be downloaded from our MURI GitHub website: <https://github.com/muriteams/gnet>.

Authors: George G. Vega Yon

similR: This R package implements several different metrics for comparing binary matrices in a vectorized way. The package is mostly based on Krackhardt's work and Choi (2010) survey paper on the issue. This is also available in our GitHub website <https://github.com/muriteams/similR> .

Authors: George G. Vega Yon, Kayla de la Haye

George G. Vega Yon, Kayla de la Haye. ergmito: Exponential Random Graph Models for Small Networks (2020). R package version 0.3-0. URL: <https://cran.r-project.org/web/packages/ergmito/index.html>
Downloads (7/27/20): 3126

Platform for Online Group Studies (POGS 2.0)

Singh et al. have continued their work in making POGS 2.0 accessible by a broader research community. They obtained open source licensing (GPL v2) from MIT and UCSB. The software, documentation for developers, and user manual are available on GitHub (<https://github.com/CCI-MIT/POGS>).

Publications

All publications associated with this MURI are uploaded into the products section.