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Network Science of Teams MURI: QUANTA – Quantitative Network-based Models of Adaptive Team Behavior (Summary Technical Report, Sep 2015–Dec 2021)

by Edward T Palazzolo

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Executive Summary

The objective of the FY15 Multidisciplinary University Research Initiative topic Network Science of Teams effort was to develop fundamental theories and build quantitative models to predict, evaluate, and simulate how teams organize, exchange information, create knowledge, influence, adapt, and reach consensus using cooperation and emergent capabilities to optimize performance. This research advanced the Network Science of Teams by creating quantitative, network-based models of adaptive team behavior through the combined disciplinary work of experts in cognitive and social psychology, computer science, control, experimental design and validation, management science, mechanical engineering, network science, organizational behavior, preventative medicine, public health, sociology, and statistics. The research team broke new ground in the learning of optimal design of teams, scaling teams to complex tasks, and advanced social science theories of team performance. Moreover, this research produced a methodology to study and optimize team performance under different contexts and resource constraints for teams with up to 50 members. They identified bottom-up approaches for improving team performance and meso-level approaches to get teams to adapt and increase their robustness. Finally, they developed top-down strategies for effectively assigning individuals to teams and teams to tasks.

1. Introduction

The FY15 Multidisciplinary University Research Initiative (MURI) topic Network Science of Teams effort titled “QUANTA: Quantitative Network-based Models of Adaptive Team Behavior,” led by Professor Ambuj Singh at the University of California, Santa Barbara (UCSB), was active from 15 September 2015 through 14 December 2021. The objective of the effort was to develop fundamental theories and build quantitative models to predict, evaluate, and simulate how teams organize, exchange information, create knowledge, influence, adapt, and reach consensus using cooperation and emergent capabilities to optimize performance. This effort advanced the Network Science of Teams by creating QUANTA through the combined disciplinary work of experts in cognitive and social psychology, computer science, control, experimental design and validation, management science, mechanical engineering, network science, organizational behavior, preventative medicine, public health, sociology, and statistics.

The overarching contributions of this research are the quantifiable informative models of team behavior as dynamical systems interacting over multiple networks that connect interaction patterns and network evolution to task performance. The research team breaks new ground in the learning of optimal design of teams, scaling teams to complex tasks, and advanced social science theories of team performance. This research produced methods to study and optimize team performance under different contexts and resource constraints. They identified bottom-up approaches for improving team performance and meso-level approaches to get teams to adapt and increase their robustness. And finally, they developed top-down strategies for effectively assigning individuals to teams and teams to tasks.

The research objectives were accomplished through disciplined focus on four thrusts over the course of the research program. Thrust 1 (Teams as Networks of Interacting Entities) focused on modeling teams as semantically labeled multilevel networks with attributes on nodes, edges, and subgroups; developed statistical models of team performance as information flows; and examined the relationship between influence networks, collective intelligence, task performance, and robustness and optimization. Thrust 2 (Analysis and Models of Dynamic Team Behavior) examined the performance of teams on a sequence of tasks; they examined changes in social influence networks resulting from repeated tasks and examined team adaptability using methods from computational learning and data-driven optimization. Thrust 3 (Network Science of Teams-of-Teams) examined the scalability of teams and tasks; they explored how to decompose a complex task into subtasks, the effect of inter-task dependencies, and how to assign teams to such tasks. Thrust 4 (Research into Human–Agent Teams) examined the means by which

computer systems can be used synergistically with humans to create more advanced teams with access to greater amounts of information and yielding improved performance.

Theories and models advanced through this MURI team's research include the following: Balance Theory, Collective Intelligence, DeGroot-Friedkin Model, Friedkin-Johnsen Opinion Dynamics Model, Multi-Armed Bandits, Network Theory, Prospect Theory, Social Influence, Social Networks, Social Power Theory, Spectral Graph Theory, Structural Balance Theory, Theory of Coordination and Control, and Transactive Memory Theory.

The Network Science of Teams MURI project was led by Professor Ambuj Singh at UCSB with the following additional team members: Professor Francesco Bullo (UCSB), Professor Noah Friedkin (UCSB), Professor Kayla de la Haye (University of Southern California), Professor Brian Uzzi (Northwestern University), and Professor Thomas Malone (Massachusetts Institute of Technology [MIT]). Total funding for this effort was \$6.76M

2. Overview of Results

From 2015 to 2021, the Network Science of Teams MURI project made efforts to enable leaders to complete the following objectives:

- 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; and
- Apply machine learning and optimization to identify new approaches that teams and organizations can use to adapt to new and unfamiliar environments.

The research program focused on four thrusts, which are summarized in Sections 2.1–2.4.

2.1 Thrust 1: Teams as Networks of Interacting Entities

In Thrust 1 (Teams as Networks of Interacting Entities), the researchers worked from the perspective of teams as semantically labeled, multilevel networks with attributes on nodes, edges, and subgroups. They developed models of team performance as both statistical models using networks and as fine-grain models of information flows and examined the relationship between influence networks and collective intelligence on task performance and considered the robustness and optimization of teams. They 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 and how an external threat changes inter-team information flows within an organization made up of many small teams. Moreover, they developed a suite of methods for extracting subnetworks that discriminate between teams with varying performance metrics, models of team performance and a characterization of their accuracy on empirical data sets, a method for analyzing transactive memory based on information flows, and a method of cognitive states of teams expanding their work on balance theory to understand how the quality of sentiments among team members influences individual and team performance.

2.2 Thrust 2: Analysis and Models of Dynamic Team Behavior

In Thrust 2 (Analysis and Models of Dynamic Team Behavior), the MURI team examined the performance of teams on a sequence of tasks, the changes in social influence networks resulting from repeated tasks, and team adaptivity using methods from computational learning and data-driven optimization.

2.3 Thrust 3: Network Science of Teams-of-Teams

In Thrust 3 (Network Science of Teams-of-Teams), the researchers 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. They considered the learning of optimal decomposition and coordination structures using methods from reinforcement learning, and they examined adaptivity over nested tasks and learning of optimal coordination structures.

2.4 Thrust 4: Research into Human-Agent Teams

Lastly, in Thrust 4 (Research into Human-Agent Teams), they conducted experiments to explore and optimize teams of humans with computer assistance.

Some of this work culminated in the book, *Superminds: The Surprising Power of People and Computers Working Together* by Dr Thomas Malone.¹

2.5 Knowledge Nuggets

At the conclusion of the project, the MURI Team provided a set of Knowledge Nuggets to offer easily understandable, high-level findings from their work. The top five knowledge nuggets are listed here.

- 1) An understanding of how teams work is incomplete without a validated model of their interpersonal influence systems.
- 2) Influence systems based on interpersonal appraisals describe the evolution of interpersonal friendly and agnostic interactions, and lead to structural balance.
- 3) Measures of collective intelligence can predict performance of teams on a variety of tasks and can be predicted by measures such as team size, cognitive diversity, and integrated information.
- 4) Strategic interactions among self-interested agents lead to hierarchical structures and to multigroup interconnections of varying density.
- 5) Structural balance correlates with performance in risky decision-making.

3. Knowledge Transitions

The Network Science of Teams MURI has achieved the following:

- Produced over 150 peer-reviewed journal articles, conference presentations, and books.
- Collected data from and shared research findings with the leadership of an Army Battalion.
- Developed novel software.
- Trained and placed 16 new PhD graduates in new jobs at various businesses and universities including Harvard, MIT, University of Illinois at Urbana-Champaign (UIUC), Google, and Amazon.
- Guided development of a start-up company for better health care.

3.1 Publications

A complete list of publications is available in the Appendix.

3.2 Fort Bragg Engagement, 92nd Civil Affairs Battalion

In 2018, three of the MURI principal investigators traveled to Fort Bragg, North Carolina, with the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL)-Army Research Office (ARO) and US Army Training and Doctrine Command representatives to meet with members of the 92nd Civil Affairs Battalion. The goals of the visit were to transfer relevant MURI research findings on team science to the 92nd Civilian Affairs Battalion and to conduct teams-of-teams research experiments (with Command, Institutional Review Board, and Human Research Protection Office approvals) to expand Transactive Memory Theory, Opinion Dynamics, and Prospect Theory. Results of the experiments were shared with the 92nd Civil Affairs Command team.

3.3 Software

Through an add-on opportunity, the Network Science of Teams MURI was able to expand their team science data collection software: Platform for Online Group Studies (**POGS 2.0**). This latest version allows for distributed data collection and testing teams of up to 50 persons (version [v] 1.0 was limited to six in-person team members). Under the leadership of Drs Malone and Singh, the team has 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.

Additionally, the MURI team developed three open-source software packages and shared them with the scientific community through GitHub.

- 1) **ergmito**: The ergmito R package implements methods for estimating and analyzing exponential random graph models for small networks using exact statistics.
- 2) **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 exponential random graph models.
- 3) **similR**: This R package implements several different metrics for comparing binary matrices in a vectorized way.

Additional details are available in the Appendix.

3.4 Job Placements Resulting from MURI Training Opportunities

In addition to exciting and substantial research created under the Network Science of Teams MURI research program, this MURI effort was also responsible for developing new Team Science scientists. Graduate students and postdocs with their post-MURI job placements are listed here.

- Agharkhar, Pushkarini: Data Software Engineer, Google; Toronto, Canada
- Amelkin, Victor: Research Scientist, Amazon; Boston, Massachusetts
- Askarisichani, Omid: Machine Learning Software Engineer, Google; Mountain View, California
- Bajpai, Kartik: Assistant Professor of Business, Emylon University; France
- Cisneros-Velarde, Pedro: Postdoc, UIUC; Illinois
- Duhaime, Erik: CEO and Co-founder, Centaur Labs
- Huang, Elizabeth: Research Engineer, Systems Technology Inc; Hawthorne, California
- Kim, Yeonjeong: Postdoctoral Associate, MIT Center for Collective Intelligence
- Kim, Young Ji: Assistant Professor, Department of Communications, UCSB; Santa Barbara, California
- Labrecque, Jennifer: Teaching Assistant Professor, Department of Psychology, Oklahoma State University; Stillwater, Oklahoma
- Lopes da Silva, Arlei: Assistant Professor, Rice University; Houston, Texas
- Medya, Sourav: Assistant Professor, Computer Science, University of Illinois Chicago; Chicago, Illinois
- Mei, Wenjun: Assistant Professor, Department of Mechanics and Engineering Science, Peking University; China
- Mohaghehi, Shadi: Navigation and Geo-Positioning Engineer, Aerospace Corporation; Los Angeles, California
- Ng, Jacqueline: Assistant Professor of Business at Harvard Business School; Cambridge, Massachusetts
- Yon, Geoge Vega: Research Assistant Professor, Division of Epidemiology, University of Utah; Salt Lake City, Utah

3.5 Human-Agent Teaming Start-up: Centaur Labs

One of the MIT PhDs trained through this MURI, Dr Erik Duhaime, is the Co-founder of a new company, Centaur Labs. This company leverages knowledge management theories for subject matter expertise with human-agent teaming for evaluating medical imaging and thereby providing earlier and more accurate detection of breast cancer, ocular degeneration, dermatological anomalies, and gut health problems. In September 2021, Centaur Labs received \$15M in venture capital funding. * Stan Reiss (Matrix Partners), stated²:

Centaur’s technology doesn’t just offer data labels, it rethinks the medical second opinion and harnesses a network of trusted experts. The ability for AI to make an impact in healthcare depends on the ability to solve the data labeling bottleneck, and Centaur will catalyze the development and adoption of AI solutions throughout the industry.

4. Conclusion

Theoretically grounded in the social sciences, the interdisciplinary Network Science of Teams MURI team produced over 100 scientific publications and delivered over 150 professional presentations. They advanced research on Balance Theory, Collective Intelligence, the DeGroot–Friedkin Model, the Friedkin–Johnsen Opinion Dynamics Model, Multi-Armed Bandits, Prospect Theory, Social Influence, Social Networks, Social Power Theory, Structural Balance Theory, and Transactive Memory Theory. Collectively, these advances in theory and methods enable the development of new and innovative tools to improve team performance in the public, private, government, and military sectors.

* <https://gritdaily.com/data-labeling-startup-centaur-labs-closes-15-mln-series-a-round/>

5. References

1. Malone T. Superminds: the surprising power of people and computers working together. Little, Brown Spark; 2018 May 15.
2. Reiss, S. Matrix Partners. Data labeling startup centaur labs closes \$15 million series a round. grit daily. 2021 Sep. <https://gritdaily.com/data-labeling-startup-centaur-labs-closes-15-mln-series-a-round/>.

Appendix. RPPR Final Report

This appendix is attached as a separate PDF file to the report. No editorial changes were made to the appendix.

List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
ARO	Army Research Office
DEVCOM	US Army Combat Capabilities Development Command
FY	fiscal year
MIT	Massachusetts Institute of Technology
MURI	Multidisciplinary University Research Initiative
POGS	Platform for Online Group Studies
QUANTA	Quantitative Network-based Models of Adaptive Team Behavior
RPPR	Research Performance Progress Report
UCSB	University of California, Santa Barbara
UIUC	University of Illinois Urbana-Champaign
v	version

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AM RAWLETT
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PJ FRANASZCZUK
C OLIVER
G BRILL
C TEETER
B PERELMAN
A SCHOFIELD
JC LANE
FCDD RLA B
A WEST
FCDD RLA CA
J FOSSACECA
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P GILLICH
FCDD RLA CC
C KRONINGER
FCDD RLA CD
J ROBINETTE

FCDD RLA CL
F FRESCONI
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D STRATIS-CULLUM
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