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DoD's Role in Network Science: NetSci Symposia on Models, Teamwork, and Education

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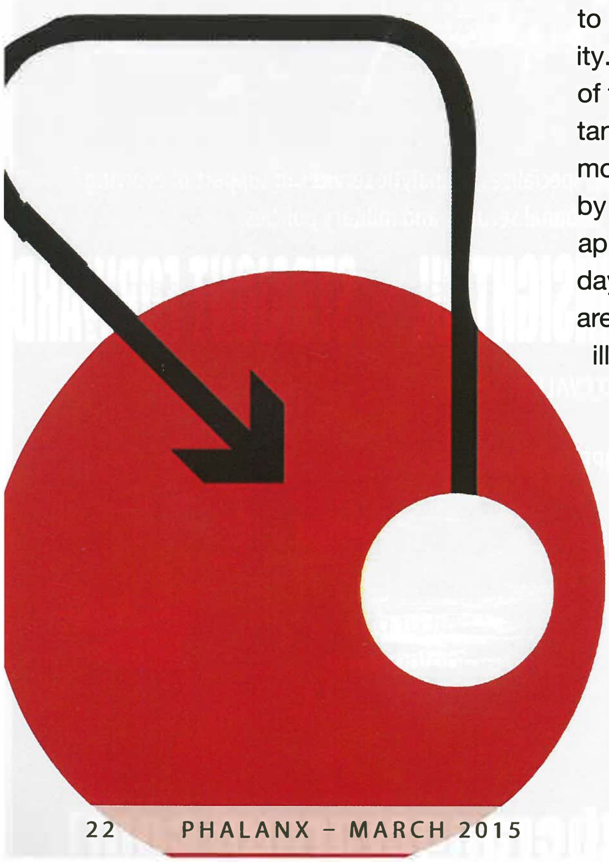
NetSci is one of the largest network science research conferences in the world and, like many network science events, researchers associated with the US Department of Defense (DoD) played a significant role in NetSci 2014. We report on three symposia held before the main conference that connected operations research and DoD applications of network science. As we describe the content of the symposia, we highlight the connections between military applications, operations research (OR), and network science (NS).

Background

The National Research Council (2005) defines Network Science (NS) as "the study of network representations of physical, biological, and social phenomena leading to predictive models of these phenomena." As stated by Eric Lang at NetSci, "DoD should care about [NS] because we spend trillions of dollars and have millions of people whose well-being we put on the line. We had better understand [NS] systems." Network modeling has enabled better awareness, analysis, and understanding for decision makers across every aspect of military operations, including communications, logistics, intelligence, training, planning, and operations. Analysts use networks to model the DoD's operational environment to provide intuition into how systems work and which elements are the most important to network functionality. Unfortunately, many of today's most important DoD networks defy modeling and analysis by traditional statistics or applied mathematics. Today's complex networks are too big, possess ill-defined organizational rules, change too much (and too fast), and manifest emergent and even chaotic properties. Into that breach steps NS.



Network science integrates multiple disciplines to understand, model, and analyze applications represented by complex dynamical networks, much like OR has taken multidisciplinary and interdisciplinary approaches to combine quantitative and qualitative methods and techniques to solve management problems. There is overlap of NS with OR. An OR analyst can describe NS in familiar terms: applied dynamic graph theory with additional attribute data, modeled as a dynamic, structured, entity-linked, interdisciplinary framework. The strength of network modeling is its ability to embrace the complexity resident in reality, making NS an empowering form of nonreductive modeling and OR problem solving (Alderson, 2008; Arney et al., 2014).

The fields of NS and OR have intertwined futures. OR is an established field and profession; NS is embryonic. To realize its potential as a contributing field, NS is reliant on its partnering with OR to establish relevance in the modern information-centric world. To grow in capability, OR is becoming reliant on NS tools for analysis of the complex structures, synergistic processes, emergent behavior, and overwhelming data that characterizes real problems. Like OR, NS merges the social, informational, communication, and physical layers of systems analysis. These multilayered networks enable a comprehensive model with multiple dimensions, tremendous volumes of data, high complexity, diversity, and specialization within the organization or system.

Complex networks are ubiquitous in the military and lie at the core of DoD systems and models including communication flow, command and control, organizational management, and information assurance implementation. Most importantly, NS helps make sense of big data structures to build the underlying knowledge base for situational awareness. The DoD has recognized the import of NS, resulting in the development of network warfare commands and research centers in each of its agencies. For example, the DoD launched a major doctrinal shift in the late 1990s based on NS called net-centric warfare (Alberts et al., 1999). As Roehner (2007) reflected, "the real challenge is to do real physics and real sociology in the framework of network theory." The three symposia from NetSci 2014 contributed to DoD's efforts to answer Roehner's challenge.

NetSci Symposium on Network Science for National Defense

Network science and other emerging data science methods are showing promise for improving understanding and analysis in US national security and intelligence missions. However, the benefit from these new analytic methods remains only in small pockets of the DoD enterprise, not spreading in a systematic way to other network-relevant mission areas in the DoD. NS needs a boost in its awareness to reach its potential to solve problems that are currently out of reach or consideration to the DoD. The exchange of ideas in this symposium was intended to be a first step in broadly exposing the DoD to the promise of NS meeting the DoD's needs, and the DoD to NS field. Symposium organizers Mark Breckenridge (OSD) and Ralucca Gera opened the discussion with a panel of network science professionals led by Jon Alt responding to general questions with an insightful view of what NS is, who does it, and what it can (and can't) do for an organization. The panel touched on several import topics:

- *Problems areas suited for NS.* Modeling is at the heart of determining which problems are suited for NS approaches. Some techniques and problems are more appropriate than others. Ideal cases for NS involve relationship data that can be described by a network. Analysts build network models not only because they are descriptive, but also explanatory—providing insight into why things are the way they are.
- *Limitations of network science.* The panel identified two significant obstacles: understanding the nature of relationships and data availability and quality. Although NS is not purely a data-driven endeavor, data are important. Because networks are characterized by interdependencies, appropriate and accurate data must be collected and processed, preserving quality in the model while reducing the noise and error.
- *Profiling a network scientist.* The panel developed a profile of skills a DoD network scientist might possess. Further discussion concluded that organizations shouldn't look for just one hypertalented scientist; rather, form NS/OR teams with certain qualities

and capabilities. Such a team must be well rounded, possessing skills in several quantitative fields and exposure to the human dimension of the application.

Several speakers followed the panel discussion, sharing network and data science practices. Summaries of two of these presentations follow.

- *A Large-Graph Comparison Measure for the Topology of the Internet* (presented by Ralucca Gera). Graph theory is a direct predecessor to complex networks. It was one of the first scientific fields to describe and explore connectedness and relationships between entities. As DoD analysts' needs transition from simple, static, and relatively small graphs to complex, dynamic, and large ones, there is a transition in thinking needed from graph theory to NS. This presentation extended traditional graph-theoretic concepts to analogous ideas in NS. For example, Figure 1 illustrates the idea of graph comparison. In graph theory, we ask if two graphs or subgraphs are the same, or isomorphic. In complex networks, we measure the level of similarity between two networks.

- *Network Science for Military Applications: Practices, Pitfalls, and Potentials* (presented by Dave Alderson). This presentation summarized prevalent pitfalls in the application of NS to system design and opportunities for NS contribution in DoD applications such as social media and other large, unstructured datasets.

Other speakers included Pete Schirmer and Douglas Yeung (RAND), Ray Zimmerman (PERSEREC), Paul Lester (RFT), and Santiago Gil (Center for Complex Networks Research at Northeastern University). The symposium concluded with a working session during which participants divided into groups to discuss relevant DoD questions. You can find a link to a summary by Jon Roginski (NPS) of the working group discussion and the symposium's proceedings on the Network Science for National Defense Symposium webpage at http://faculty.nps.edu/rgera/conferences/NetSci2014/dist/. This symposium increased awareness of the potential for NS techniques to impact more areas of DoD operations. The symposium plans to convene again yearly to discuss additional DoD-relevant topics, further spread NS and OR awareness and compatibility, and chart the way forward for greater analytical support to national defense.

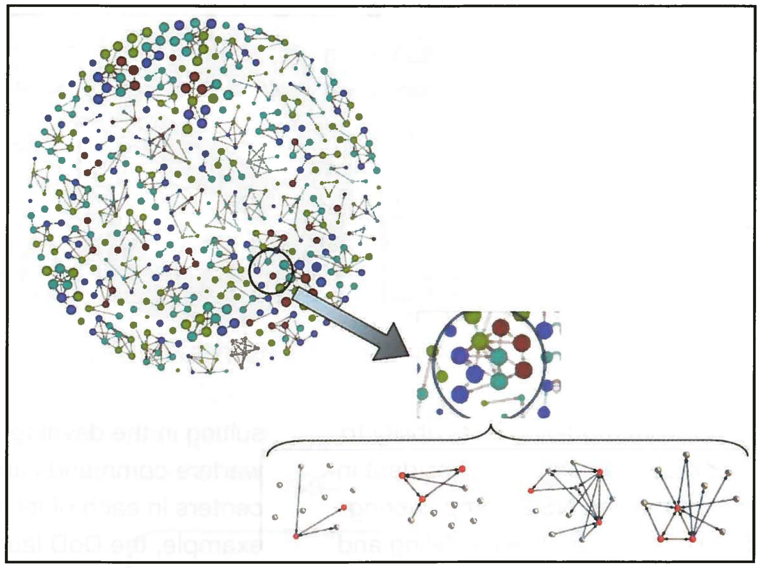


Figure 1. Graph theoretic vs. complex network measures.

NetSci Symposium on Team Networks

Examples abound in which teams perform better than groups of individuals—even when the individuals are more skilled than single members of the team. Researchers and practitioners speculate that the success of teams stems in part from their multidisciplinarity and their ability to assimilate, reinforce, and recombine knowledge and talent (Uzzi et al., 2013). The enhanced capacity of team performance over individual suggests there is potential for moving the boundaries of human achievement forward through more and better use of teamwork in networked organizations.

Yet, knowledge about what factors are the primary drivers of success or how these drivers operate remains nascent. The NetSci Symposium on Teams sought to develop a framework for creating formalized theory, improved metrics, and viable models of team dynamics. Discussed at the symposium were recent developments in team-related cognitive science (team cognition), industrial and organizational psychology (science of team science), computer science and statistics (science of success), and management. The symposium's conclusion was that this topic is ripe for exploration as an integral part of DoD organizational and doctrinal development. Team networks enable groups of people to build knowledge, reach consensus, achieve breakthroughs, and generally perform complex problem solving that would not be attainable through either individual efforts or a sequence of additive contributions. A critical question in the military is how to improve the performance of teams and of multiteam systems (teams that work together to carry out missions).

Symposium organizers Kate Coronges and Chris Arney brought together several academic communities—network scientists, team and communication scientists, cooperative systems scientists, and game theorists, many with DoD connections. Noshir Contactor (Northwestern) and Alice Leung (Raytheon BBN) presented frameworks to conduct social experiments in multi-team systems. Experimental data on communication activity reveals motifs or patterns of activity (shown in Figure 2) that can be used as explanatory variables to model team processes (dynamics) and outcomes (e.g., performance). Elisha Peterson (Applied Physics Lab) presented a group-level game theoretic framework based on Shapley theory, which teases out the rationality of the individual versus the rationality of the group. Measures of a person's individual contribution to the group using various subset boundaries can assess altruism and competition within team members. Darryl Ahner (Air Force Institute of Technology) presented a model of information need and sharing based on Miller, Miller, and Shattuck (2007) situated cognition model. Leslie DeChurch (Georgia Tech) gave the plenary talk on "Leadership and Networks." Two panel sessions predicting the future of team collaboration processes models, one from a mathematical modeling perspective and the second based in the social and behavioral sciences, concluded the workshop.

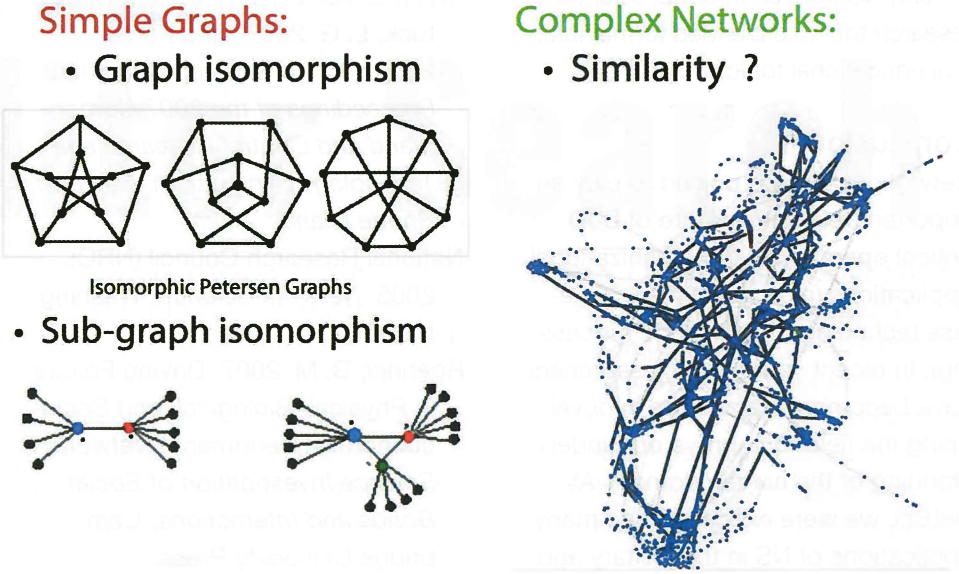


Figure 2. Motifs or patterns of activity are identified during field experiments or computer games and used to predict team dynamics and performance outcomes. This figure demonstrates motifs as presented by Leslie DeChurch at the conference.

NetSci Symposium on Education

Due to the complexity of today's operational environment, it is essential that future leaders, including military, are able to naturally leverage the connectivity of disciplines rather than reducing problems into pieces or groupings that are addressed individually with traditional "stove piped" disciplinary expertise. In anticipation of preparing the next generation to operate effectively in the complex, networked environment, a group of educators have been harnessing students' inherent interest in networks to engage them in interdisciplinary problem solving.

The NetSciEd Symposium, organized by Catherine Cramer and Stephen Uzzo of New York Hall of Science, Hiroki Sayama from Binghamton University, and Gene Stanley and Paul Trunfio from Boston University, and Lori Sheetz, focused on NS teaching and learning at all levels of formal and informal education. Topics discussed were:

- Teaching teachers network science concepts
- Network science in K-16 practice and policy
- Network science in the military
- Network science in informal education
- Tools for teaching network science
- New directions in learning science
- Developing metrics for effective educational collaboration networks
- Applying network science concepts to the Common Core framework.

Speakers included Mason Porter (University of Oxford), Toshihiro Tanizawa (Kochi National College of Technology, Japan), Brooke Foucault Welles (Northeastern University), and Robin Wilkins (UNC Greensboro).

Components of networks have been used as a tool for teaching math, computer science, and technology for many years. More recently, network scientists have expanded these efforts by developing and sharing informal outreach materials to demonstrate how NS can successfully be used to engage students in STEM fields (Harrington et al., 2013; Sanchez and Brandle, 2014) and to learn problem-solving skills. These successes led to a model in which NS is used to teach abstract concepts within formal education settings including the Common Core Learning Standards. Lori Sheetz presented her model for bringing NS into high school STEM curricula. Her educational framework was developed from working with teachers and school administrators by shifting NS from an informal science research tool to a blended formal/informal educational topic.

Conclusion

Network science is poised to play an important role in the future of DoD critical operational and organizational applications (e.g., net warfare, wireless technology, intelligence processing). In recent years, DoD researchers have become a major force in developing the field to improve our understanding of the human domain. At NetSci, we were excited to see many applications of NS in the military and evidence of its ties and relationships to OR with an emphasis on situational awareness, learning and teaching strategies, and organizational dynamics. DoD has played a significant role supporting NS research and, based on what we heard at these three symposia, NS will continue to play significant roles in the future of DoD.

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About the Authors

Chris Arney is a network mathematician serving as professor of mathematics and chair of network science at the United States Military Academy. After serving 30 years in the Army and four years as a dean at a university, he was a program manager at the Army Research Office. He enjoys teaching mathematics and network science and advising cadet research projects. He is the president of the Military Applications Society, INFORMS.

Kate Coronges received a master's degree in public health and a PhD in human health behavior from the University of Southern California. She is an assistant professor in the Department of Behavioral Sciences & Leadership and a research fellow in the Network Science Center at United States Military Academy, West Point, New York. Currently, she also serves as a program manager at the Army Research Office. Her research interests focus on the role of social and organizational network structures, and the dynamics of these networks, in communication patterns and performance of teams, groups, and societies.

Ralucca Gera is an associate professor of mathematics and the program manager for the Academic Certificate in Network Science at the Naval Postgraduate School. Her research interests are in graph theory and recently in complex networks, with applications to the study of the Internet's topology as well as natural language processing. She enjoys teaching and working on research projects with US and international officers at NPS in Monterey.

Lieutenant Colonel Jon Roginski, US Army, is currently a PhD student in the Department of Applied Mathematics at the Naval Postgraduate School. He holds an MS from the Naval Postgraduate School and a BS from the United States Military Academy, West Point, New York. LTC Roginski has served as an operations research/systems analyst with the 10th Mountain Division while deployed in support of Operation Enduring Freedom and while in home station. He also taught mathematics and ethics at the US Military Academy and served as a military police officer at Fort Drum, New York, and Torii Station, Okinawa, Japan.

Lori Sheetz does outreach and education research at the Network Science Center at West Point. For the past four years she has used her science and education background to bring the new field of network science to middle and high school students from around the United States through STEM workshops and yearlong research projects. She enjoys engaging students in STEM topics using the framework of networks, technology tools, and drawing on student insights gained through the prevalent adolescent use of social networks.