Network Science Center at West Point

*Advancing the Study of Network Science*

**PAPERS OF THE 5TH ANNUAL NETWORK SCIENCE WORKSHOP**

**26-28 OCTOBER 2010, WEST POINT, NEW YORK**

# THE ARMY'S NETWORK SCIENCE NEEDS AND OPPORTUNITIES: REALIZING THE POTENTIAL OF NETWORK SCIENCE THROUGH THE NRC RECOMMENDATIONS

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**Introduction:** In 2005, a select committee of distinguished scientists assembled by the National Research Council (NRC) wrote: "Today, there is no coherent discipline for the study of networks. A well-defined science of networks would provide a much more efficient path to a fully capable network-centric force." [NCR Report 2005] Five years later, the Army has made great strides in defining and formulating the emerging science of networks and this effort is having impact on today's net-centric operations. The call to action initiated by John Parmentola, then the Director for Research and Laboratory Management in the Assistant Secretary of the Army for Acquisition, logistics, and Technology (ASA(ALT)), through the NRC committee has resulted in numerous Army research laboratories and program funding agencies contributing to this new science. We outline the original call to action and summarize the progress that the Army has made in this new emerging science along with its operational impact. This paper focuses on the US Army's research effort and its contributions to the discovery of a network science (NS). The Army's network science research enterprise has its goal: "An Army-led effort to realize a network science to enable Network Centric Warfare through the incorporation of interdependency and networked human and organizational behavior leading to effective employment of the full spectrum of C4ISR technologies." [Parmentola (2007)] While network science examines the interconnections among physical networks, communication networks, information networks, biological networks, social/cognitive networks; the overall field of network science seeks to discover common principles, algorithms and tools that govern network behavior and allow for prediction of performance and utility.

**Army's Network Science Definition and Goal:** The Army's NS approach focuses on the soldier's needs and the Army's Net-Centric Warfare capabilities including information propagation and fusion, modeling and analysis of very large networks, design of effective networks, decision making, development of measurements of network structure and metrics for network processes. The Army's NS research seeks to understand how distributed teams behave and how these teams can collaborate to make synergistic or synchronized decision, to determine

how to assess a large variety of disparate sources of information with unknown pedigree and veracity, and to focus on the behavior of complex adaptive systems, emergent properties of small semi-autonomous forces, and effects of culture on perceptions and behaviors. Information principles and metrics for new complex dynamic (mobile, ad hoc) networks (MANETs) and the techniques for mining textual data for intelligence processing need to be developed.

**Army's Network Science History:** A brief look at the history of network science and the Army's role in its development can be shown through a chronology of several significant publications and authors:

***1736***: *Seven Bridges of Königsberg* by Leonhard Euler --- The first rigorous theory of networks using graphs.

***1959***: "On Random Graphs" by Paul Erdős – This work produced the first theory of random graphs, combining probability and stochasric process with graph theory.

***1981****: The Evolution of Cooperation* by Robert Axelrod (and the follow-up in 1997: *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration*) – This book linked game theory and social networks. It also established theories about the role of individuals in groups, using a cooperative approach including altruism and collaboration.

***1999:*** *Network Centric Warfare: Developing and Leveraging Information Superiority* by David Alberts, John Garstka, and Frederick Stein – The book set in motion the idea of using information networks as force multipliers to enable more potent and effective operations.

***2002****: Linked: How Everything is Connected to Everything Else and What is Means for Business, Science, and Everyday Life* by Albert-Laszlo Barabasi – This book introduced the concept of scale-free networks and explained their presence in natural, technological and social systems, from cell phones to other social networks.

***2003****: Six Degrees: The Science of the Connected Age* by Duncan J. Watts – This book introduced small-world networks and refined the theory of scale-free networks. It also discussed new network properties involving social decision making and thresholds in networks.

***2004****: Sync: The Emerging Science of Spontaneous Order* by Steven Strogatz --- This book discusses the synchronization in dynamical systems and networks, especially biological systems.

***2006:*** *Fm 3-24: Counterinsurgency* (by David Patraeus along with many other authors including James N. Mattis) – This book contains a new military philosophy for counterinsurgency that recognizes the power of networks for both the insurgents and counter-insurgents. As a follow-up to this book, he wrote an article in the Sep/Oct 2008 edition of *Military Review* entitled "Commander's Counterinsurgency Guidance." In this book, Patreaus gives a NS perspective for the counterinsurgency warfighter that includes setting its context: "The network organization is a new concept in our military lexicon but an old concept in application. Whether in insurgent groups or business organizations we expect the network organization to become the norm. Unfortunately, given the flexibility, speed, & connectedness in a network organization, organizational behaviors can rapidly become an invisible box with hidden connections &

transactions. The network organization has a different pulse than an organization tied to strict procedural norms and expectations. Further, the network organization inherently deletes or bypasses stovepipes that slow or inhibit decision making & coordination. Insurgents are a network organization embedded in a sympathetic population. Differentiating between the insurgent, the insurgent-supporting population, the neutral population, and the friendly population is difficult. SNA (Social Network Analysis) assists with formalizing the informality of an insurgent network; with visualizing a structure that we may not readily observe. Network concepts allow us to highlight the structure of a previously unobserved association. By focusing on the roles & organizational positions of those actors who are prominent or influential, we get a sense of how the association is structured & thus how the group functions, how members are influenced & power is exerted, & how resources are exchanged." [Patraeus (2006]

***2008:*** *Hot, Flat, and Crowded* by Thomas L. Friedman – While this book does not emphasize the role of networks in the author's vision of a greener, connected, more global world, science plays a major role in his view of interdependence and network science development is needed to fulfill his vision. Friedman's description of a system is network science. "The first rule of systems is that everything is connected to everything else, the second rule is: You can optimize individual pieces only up to a point. If you don't scrap the old system and put a new system in place, ultimately everything you do will be constrained. But if you put together a new system, and you do it right [network science], everything starts to get better." [Friedman (2008), p. 185]

**Army's Network Science Vision:** The basic model used to visualize the Army's networked approach (shown in Figure 1) contains four layers in order to: [NRC, 2005]

- Model, analyze, predict, and control the behavior of networks
- Understand linkages and interactions among network domains
- Enable humans to effectively exploit information for timely, effective decision making
- Drive design of robust networks that align with human cognitive capabilities

These layers shown in the diagram of Figure 1.

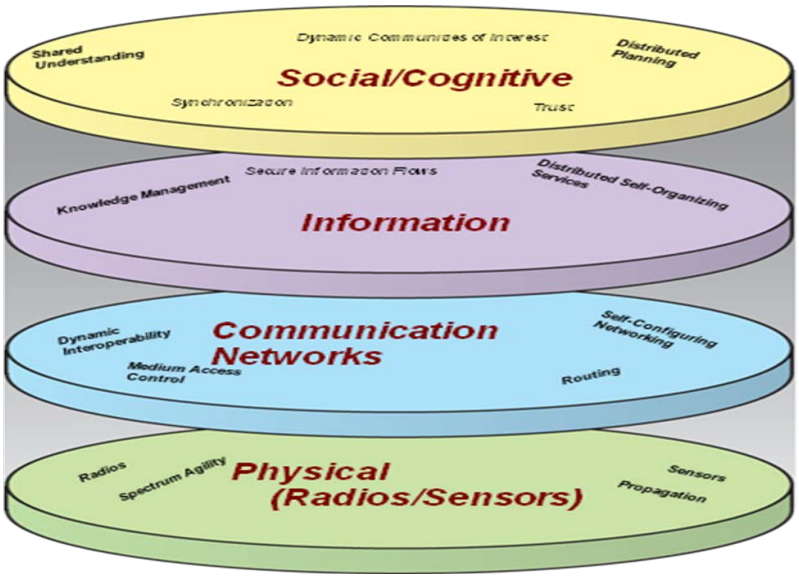

Figure 1: The layered model of Army's network science research from NRC Report

**NRC Call to Action**: The NRC panel through their recommendations charged the Army to support network science research. The panel's recommendations included: [NRC Report (2005)]

- The Army should make a modest investment of at least $10 million per year to support a diverse portfolio of basic network research that promises high leverage.
- The Army should fund a basic research program to explore the interaction between information networks & the social networks that utilize them.
- The Army should underwrite a broad network research initiative that includes resources for both military & nonmilitary applications.
- Strengthen the theoretical underpinnings of network science.
- Conduct basic research on how and why biological and social (non-physical) networks function and determine their applications to military networks.
- Focus applied S&T to enable social networks important to Army operations.

**NRC Network Science Research Areas:** Research supported by the Army has made advances in the following NRC network science research areas (see Figure 2): [NRC Report (2005)]

- Modeling, simulating, testing, and prototyping very large networks
- Command and control of joint/combined networked forces
- Impact of network structure on organizational behavior
- Relationship of network structure to scalability and reliability
- Managing network complexity
- Improving shared situational awareness of self-synchronization networked elements
- Enhanced network-centric mission effectiveness
- Advanced network-based sensor fusion
- Hunter-prey relationships
- Swarming behavior

**NRC Network Science Research Challenges:** Similarly, the Army's program has confronted issues in all the major research challenges developed by the NRC: [NRC Report (2005)]

- Dynamics, spatial location, and information propagation in networks.
- Modeling and analysis of very large networks.
- Design and synthesis of networks.
- Increasing the level of rigor and mathematical structure.
- Abstracting common concepts across fields.
- Better experiments and measurements of network structure.

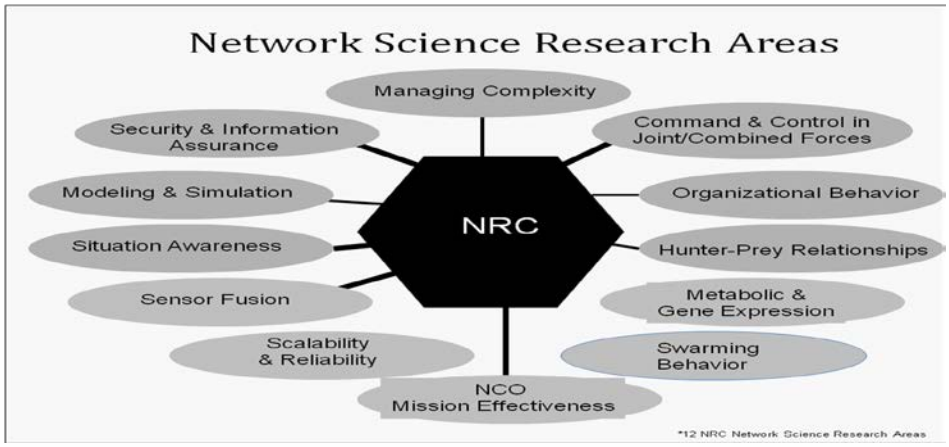


Figure 2: The NRC's categorization of NS research areas. [NRC Report (2005)]

**The Army's Progress:** Some of the progress falls in these areas [NSTC (2008)]:

- **Multi-agent networked control (**Advance understanding and control of collections of agents and autonomous teams)
- **Intelligent networks (**Advance understanding of information transfer among complex networks to include developing situational awareness)
- **Decision & neuro-Sciences (**Principles for decision making and forecasting in complex heterogeneous environments)
- **Communications & human networks (**Advance understanding of human-communications network interaction in MANETs)
- **Mathematical models of network behavior to predict performance with network size, complexity, and environment** (Optimized human performance required for network-enabled warfare.)
- **New protocols for routing, scheduling, and synchronizing sensor networks**.
- **Tractable, approximate solutions to optimization problems** (This work on graphical models for data fusion allows for situational awareness, multi-target tracking, and distributed processing.)
- **Wireless sensor networks that reduce their power consumption**. (These results set the stage for further work aimed at revealing the fundamental tradeoff between the performance and power/bandwidth consumption in wireless sensor networks and for network science overall.)
- **Architectures for detecting cyber attacks have been developed**. (Detection algorithms have been developed that utilize this architecture.)

**The Army's Network Science Research Projects:** Under the leadership of many managers, scientists, and leaders, the following agencies are actively conducting or supporting significant network science research:

- **Army Research Office's Information Sciences Directorate** This organization consisting of three divisions (mathematics, computing science, and network science --- newly added in 2008) is able to manage research in all areas of the NRC report and

integrates research in mathematics, statistics, computation, complexity modeling, behavioral science, computer science, and information science to build the foundations and principles for network science.

- **Army Research Laboratory's Network Sciences Division** This new Division of the Computer and Information Directorate seeks to build models for MANETs as ARL scientists research complex dynamics that occur in interactions of different genres of networks: social-cognitive, information and communications. These new insights will help design, compose, predict, and control networks to increase the Army mission effectiveness. In the Cyber Defense arena, ARL develops novel techniques and tools that counter evolving cyber threats to both conventional and mobile networks, recognize malware, and enable forensic analysis cyber attacks.
- **Army Research Institute for the Behavioral and Social Sciences** This organization seeks to support innovative behavioral science research to understand the relationships among physical and human networks; command organizations; and individual, unit, and organizational behavior within context of complex networked environments.
- **Network Science Collaborative Technology Alliance** (CTA). The CTA is made up of four centers designed to work closely together. The Information Networks Academic Research Center is led by the University of Illinois-Urbana Champaign, the Communications Networks Academic Research Center is led by Penn State University, the Social-Cognitive Networks Research Center is led by Rensselaer Polytechnic Institute, and the Interdisciplinary Research Center is led by Raytheon BBN Technologies. This is the major center called for by the NRC Report.
- **International Technology Alliance** (ITA) in Network and Information Science. In 2006, the U.S. and the United Kingdom (UK) formed the Network and Information Science International Technology Alliance, a partnership among the Army Research Laboratory, UK Ministry of Defense and a consortium of industries and universities. The goal of the alliance is to perform basic research in support of Network- Centric Operations and in particular explore the neural representations of command-level decision-making to identify most important factors and validate neural processing associated with using networked information.
- **Institute for Creative Technologies** (ICT) This organization creates immersive environments through full sensory immersion and three-dimensional mobility with interactive stories that show the value and networking and communicating.
- **Institute for Collaborative Biotechnologies** (ICB) In network science, ICT studies biologically derived sensors, electronics, and information processing.
- **Communications-Electronics Research, Development, and Engineering Center** CERDEC seeks to develop and integrate command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) technologies that enable information dominance and decisive lethality for the networked warfighter.
- **West Point Network Science Center** In 2004, the Department of Defense established its first Network Science Center at the United States Military Academy. This organization has tremendous outreach to the Field Army and is a natural conduit for research to impact the operational Army. In addition to hosting workshops, the research includes Biological Networks, Flowing Valued Information, Frontier Markets, Social Network

Analysis, Statistical Changes, Actor Oriented Models to Detect Significant Behavioral and Social Changes Over Time, and Network Structures and Algorithms.

**Field Army Applications:** In many ways, our new COIN tactics and strategies reflect our NS progress. FM 3-24, written by General Patraeus, contains many examples of network science advances being leveraged by the Field Army. The following passages are directly from that book: [Patraeus (2006)]

> "The purpose of network analysis is to provide commanders with an understanding of the insurgency and what is driving it. Network analysis requires a large investment of time. Analysts may have to spend months going through large amounts of intelligence in order to provide an accurate picture of insurgent groups. The investment is worth it. The more accurate and thorough the intelligence, the more effective friendly operations become. It is easy for intelligence personnel to be drawn into current operations. However, commanders must ensure that network analysis occurs. The tasks of network analysts are to:
>
> - Identify insurgent goals and motivations.
> - Identify the grievances exploited by insurgents.
> - Determine how culture, interests, & history inform insurgent decision making.
> - Understand links between political, religious, tribal, criminal, & other social networks.
> - Determine how various networks and groups interact with insurgent networks.
> - Determine the structure and function of insurgent organizations.
>
> **Social Network Analysis**: Social network analysis (SNA) is characterized by a distinct and unique methodology for collecting data, performing statistical analysis, & making visual representations. Such applications can be useful for devising effective schemes for promoting ideas or exerting influence in organizations. These are important functions, but the relevance of such analysis to counterinsurgency (COIN) primarily deals with explaining how people behave & how that behavior is affected by their relationships."

A schematic diagram of how this can work for the density property of a network is shown in Figure 3.

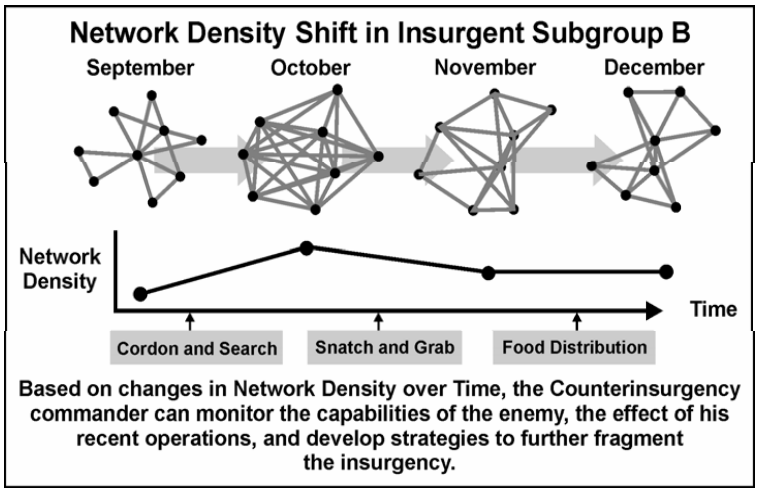


Figure 3: A network schematic showing how network analysis can affect the operations of an insurgency. [Patraeus (2006)]

**Conclusion:** The NRC panel was insightful in understanding the current state and future potential of network science, establishing meaningful research areas and challenges, and making bold, yet doable recommendations in a broad spectrum of potential network science research areas. Similarly, the Army research community has been equally insightful in implementing a rigorous, multi-agency, extensive program to advance the science and solve the first-level challenges. The Army must also be commended for its innovative use of NS in the Field Army, especially in COIN operations. FM 3-24 is a remarkable document in its application of NS to explain insurgencies and social network analysis. NS went from a theoretical idea in 2005 to a Army doctrinal concept just two years later. However, the most amazing story of Army NS is just how far the research supported and performed by the Army has taken NS in just five years. The Army reorganized and reprioritized its efforts and these actions have paid off in many significant advances. The foundation of a new science has been built and a network science is emerging. Five years ago NS was a vague cloud of multi-disciplinary ideas, today it is a focused interdisciplinary effort with emerging theory and underlying concepts far more advanced than when Duncan Watts wrote "The progress of time … has made the science of networks more, not less, relevant to the affairs of the world". [Watts (2003)] While the future of NS is yet to be written, it is safe to predict NS is here to stay and its emergence as a science will continue to have great impact on the Army.

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