

13th ICCRTS

“C2 for Complex Endeavors”

Title: “The Human Dimension of Networks”

Topics:

Concepts, Theory, and Policy
Networks and Networking
Organizational Issues

Authors:

Bruce J. West Ph.D.
Army Research Office

Elizabeth K. Bowman Ph.D.
Army Research Laboratory – Human Research and Engineering Directorate

Brian Rivera Ph.D.
Army Research Laboratory – Computer and Information Sciences Directorate

Point of Contact:
Elizabeth K. Bowman
AMSRD-ARL-HR
Building 459, Aberdeen Proving Ground, MD 21005
410-278-5924
EBowman@arl.army.mil

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE JUN 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE The Human Dimension of Networks		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Army Research Laboratory, Human Research and Engineering Directorate, AMSRD-ARL-HR, Aberdeen Proving Ground, MD, 21005		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES 13th International Command and Control Research and Technology Symposia (ICCRTS 2008), 17-19 Jun 2008, Seattle, WA					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 32	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

The Human Dimension of Networks

Abstract

This paper describes a research plan that will examine the linkage between the physical and human (cognitive and social) domains of a network as they relate to human decision-making. This strategy has three components: theory, computation/simulation and experiment/observation. We will extend the most recent methods of statistical physics to non-stationary, renewal stochastic processes that appear to be characteristic of the interactions among nodes in complex networks and we will pursue the phenomenon of synchronization, whose mathematical formulation has recently provided insight into how complex networks reach accommodation and cooperation. The theoretical analyses of complex networks often elude analytic solutions and require large-scale simulation and computation to analyze the underlying dynamic process. We will use agent-based modeling to simulate the dynamics of such complex networks, particularly models of dynamic decision-making under conflicting constraints and with incomplete information. We will develop decision-making scenarios from which to extract large amounts of data for analysis, for the development of theoretical models and the construction of large-scale computer simulations, as well as, optimal data processing techniques to guide the theoretical analysis. We expect that the theory, computation/simulation and experiment/observation components will inform and refine one another in an iterative way through intense collaboration.

1. Introduction

Modern society is more interconnected than humanity has been at any time in world history. A western city could not function without garbage collection, interconnected sewers, electricity from the power grid, transportation networks, food distribution networks, health care networks and would have a very different form if it did not have networks of education, banking, telephone service and the Internet. Some of these support networks within the city are physical, others are social and their forms have been evolving for millennia. Part of that evolution was the development of their interoperability such that these networks are all interconnected and in one way or another they connect to national and/or global networks.[i] This network-of-networks (NoN) is the engineered webbing of humanity, but there are comparable structures in the biosphere and ecosphere involving plant and animal NoN of unlimited variety. Clues to understanding human-based complex adaptive networks¹ (CAN) may be found in naturally occurring CANs.

This modernity is manifest in the military through the development of Network-Centric Warfare (NCW) which takes cognizance of human behavior in a networked environment of organized actions, often violent, directed toward political ends [ii] and is the basis of a new theory of war. Thus, NCW is at the heart of force transformation and has at its core a shift in focus from the platform to the network of which the platform is a member. Thus, Army scientists need to understand the dynamics, controllability and predictability of generic nonlinear complex

¹ Note that this definition is related to, but is distinct from, complex adaptive systems (CAS) introduced in the literature on complex dynamical systems. This is different from the more traditional use of computers, which is to ‘merely’ evaluate theoretical predictions and process data.

networks in order to realize their goal of supporting the soldier through research and the development of new technologies.

It is not only our external world that is cluttered with networks, but our internal world as well. The neuronal network carrying the brain's signal to the body's physiological networks is even more complex than the modern city or a typical ecological network. Consequently it is premature to assign preeminence to any one CAN or collection of CANs from any particular discipline before we understand the patterns formed by the multiple interactions within and among them. Thus, the basic research into network science must span a multitude of disciplines.

The problem we address in the proposed research plan for this first Army Science Objective (ASO) is to develop the basic research foundation of a science of networks supporting the linkage between the physical and human (cognitive and social) domains as they relate to human decision-making, particularly within the Army's command and control structure. This proposal is not directed at the totality of developing a Network Science, but has the more modest goal of understanding the deeply interdependent physical and human networks of crucial importance to the Army. Even such a restricted problem is a significant challenge due to the multiply interconnecting networks buttressing the common decision making objective; the proposed research is to uncover this interconnectedness of the human and physical CANs, in order to control them and make predictions. Achieving this goal requires in-depth collaboration of scientists from multiple disciplines, so the proposed ASO will provide a well-defined context for the Army Research Laboratory scientists in the Computer and Information Science Directorate (CISD); the Human Research Engineering Directorate (HRED); the Army Research Office (ARO), as well as other ARL scientists, to focus on the interactions of the networked human, information and communication domains.

On the one hand, defense transformation is proactive in that networked forces can operate in an agile manner to promote decision-making superiority. On the other hand, defense transformation is reactive in the need to respond to enemies who are also using the power of networks against United States interests. The proposed research conducted within this ASO should provide insight to allow the Army to anticipate the enemy's use of network strategy and thereby reduce the reactive mode of operation. Consequently, we need to proceed by identifying what is presently known about complex networks, regardless of the disciplinary context and adapt that understanding to the decision-making paradigm within the military. Moreover, the barriers to further understanding and the gaps in knowledge of the linkages between physical and human decision-making networks need to be addressed.

The research strategy described in this paper is based on the interaction of theory, computation/simulation and experiment/observation. This is a cyclic interactive process in which new theory stimulates unique simulations, yielding insight into parameter values and network configurations, which in turn suggests specific experiments, whose outcome guides the refinement and development of the theory. This modern approach to scientific research² is applied to the phenomenon of human decision-making in Network-Centric Warfare. The ARL researchers having expertise in these three broadly defined areas propose to work collaboratively to define an expanding program to encompass emerging in-house, university and industrial research. The core group of Army scientists will be the focal point for external researchers requiring militarily relevant challenges and internal ARL efforts.

2. Background

² Note that what makes this approach modern is the inclusion of computation/simulation in the iterative scientific process that historically included only theory and experiment.

The pace of growth of information and communication technology, along with network capabilities is driving fundamental conceptual changes in United States and coalition defense doctrine. Three of the critical drivers of this change are the information, communication and social networks, which have worked symbiotically to foster the changes in the nature of military operations. Certainly these three networks taken separately do not constitute new phenomena. Twenty five years ago social networks were fairly stable, being maintained by communication over telephone and mailing networks, and supported by libraries and other information archives. Today, social network are ephemeral, with virtual interactions in cyberspace chat rooms, information being supplied by Wikipedia and all available through Google. Social networks are large, ad hoc, and maintained in real time by the Internet services and cell phone technology. While in previous decades it would have been unthinkable for the average soldier to circumvent the chain of command and address his/her concerns directly to a general officer, the modern day computer with the network of emails actually invites such interactions.

The proposed ASO program promotes basic research investigations into how these networks in the greater society are driving changes in the Army's information, communication and social domains and how these changes, in turn, influence and adapt decision-making in the command and control structure of the military.

2.1 Need for Network Centric Warfare

There has been an avalanche of research into a variety of phenomena described as networks over the past five years, but the recognition of the need for an overarching science of networks is of even more recent vintage [1]. The DoD description of NCW asserts it to be a consequence of the social transformation from the age of the machine to the age of information [3]. However information is only one aspect of force transformation. A more encompassing view arises by acknowledging NCW to be the result of the transformation from the information age to the age of connectivity, a view more in keeping with networks. Consequently, we need to go beyond accepting the four tenants of NCW as a working hypothesis [2]:

1. A robustly networked force improves information sharing.
2. Information sharing enhances the quality of information and shared situational awareness.
3. Shared situational awareness enables collaboration and self-synchronization, and enhances sustainability and speed of command.
4. These, in turn, dramatically increase mission effectiveness.

Although, intuitively reasonable, these four tenants have proven difficult for researchers to validate. A science of networks is in fact needed to establish their degree of validity. Moreover, the implications of these suppositions could be rigorously explored and used to clarify the new rules by which NCW forces the Army to organize, train and operate.

NCW or Network Centric Operations (NCO), represents a shift from platform-centric warfare to a networked information superiority capability. Information superiority is defined as a state achieved when a competitive advantage is derived from the ability to exploit a superior information position. Information superiority is intended to generate increased combat power by networking networks, decision makers, and shooters to achieve shared awareness. This awareness will increase the speed of command to enable a higher operational tempo, ensure greater lethality and increased survivability, and ensure self-synchronization of force elements. The network is the means by which these knowledgeable entities on the battlefield are linked.

There is also a statement of governing principles [2] for NCW, but like the four tenants, these too are essentially philosophical in nature. Although the arguments for these principles are logically consistent and intuitively attractive, the principles themselves have neither an empirical nor scientific basis. An attempt at providing an empirical basis was given [iii], but this analysis took the form of case studies, and did not rise to the level of systematic laboratory or field

observations capable of making or testing predictions. This report emphasized that NCO is not about hardware, rather it is about people, organizations and processes. While this is true, NCO is also about the hardware that enables the flow of information that interconnects these networks.

2.2 What we know about networks

To frame the research proposed herein we briefly review our limited knowledge of the basic properties of certain complex networks, starting with the simplest, in which the connections among the nodes (the fundamental elements of the network) are random. Random networks are static and although they do demonstrate a number of interesting properties, they are too restrictive to mimic the full range of behaviors of most real-world phenomena. Random networks are characterized by average quantities. Two real-world properties that random networks do *not* capture are growth and the criteria for establishing new connections in growing networks. *Preferential attachment* is a rule by which newly formed nodes prefer to make connections to nodes having the greatest number of existing connections within a network. This rule, along with growth, is sufficient to develop an understanding of a class of scale-free networks. Such scale-free networks have inverse power-law distributions in the number of connections to a given node. There is a deep relationship between these scale-free networks and fractal statistics, for a more complete discussion see, for example, West [iv].

The question arises as to why scaling networks appear in such a variety of contexts; biological, chemical, economic, social, physical and physiological. Answers to this question have been found independently by a number of investigators and are all of a similar nature. In the case of the human lung West [v] determined that a physiological fractal network was preadapted to errors, is unresponsive to random perturbations and therefore has a decided evolutionary advantage. The evolutionary advantage would lead one to expect to find inverse power laws in all manner of biological phenomena, which we do. A decade later a similar result was found for scaling networks, for example, the Internet was shown to be fairly unresponsive to either random attacks or random failures [vi]. An inverse power law in the number of links implies a large number of nodes with relatively few connections, but a non-negligible number of nodes could be considered to be *hubs*. Consequently, random attacks on such networks would most likely destroy or disrupt nodes with only a few connections and therefore have negligible effect. The likelihood of striking a hub at random and thereby having a global effect is relatively small. Therefore the scale-free network is robust against random attacks. It is this tolerance to local attack (failure) that gives rise to the robustness of scale-free networks and this tolerance is a consequence of the architecture of the network.

The scale-free network and fractal physiological structures both have an evolutionary advantage because of their fractal properties. On the other hand, such networks are susceptible to attacks directed at hubs, and elimination of only one or two of these hubs could produce catastrophic failure of the network. It is this later strategy that is adopted by terrorists, when these most sensitive elements of the network can be identified and attacked [6].

The scale-free network formalism was constructed using a combination of data analysis, reasonable arguments concerning the interactions among individuals in a social network and mathematical modeling. The distribution of network connections resulting from this process was inverse power law in agreement with observation. A completely different approach was taken by Carlson and Doyle [vii], who wanted to know what kind of control process was necessary to design a network having the inverse power-law behavior. This is an engineering approach in which the constraints on the design of the network must be specified. Although both approaches result in inverse power-law distributions in agreement with data, other properties of the network are remarkably different.

The HOT³ procedure is intended to provide robust network performance in the face of environmental uncertainties and replaces scale-free with scale-rich networks. This engineering perspective forces power laws in specified network properties through tradeoffs between yield, cost of resources and tolerance of risks. The result is a “robust, yet fragile” network behavior. The difference between scale-free and scale-rich is that in the former large fluctuations emerge and recede as a natural consequence of the internal dynamics. Consequently the network is robust. On the other hand, the latter network is hypersensitive to new perturbations that were not part of the design; so that the HOT network is robust, yet fragile. It should be emphasized that both types of networks have their Achilles’ heels. How to identify these weaknesses and design around them is one of the remaining challenges.

It has been determined that inverse power laws are ubiquitous in complex networks, arising in every context from the smallest molecular level to the largest social gathering. Moreover the existence of such inverse power-law statistics emphasizes the differences between simple networks that can be described by the statistics of Gauss and the complex networks which cannot. However, knowing the statistics of a network to be inverse power law is not sufficient to understand the underlying generating mechanisms. We need to identify the mathematical and experimental/observational problems whose solutions can contribute in a substantial way to the development of the measures required to separate and categorized inverse power laws according to their generating mechanisms.

2.3 What we do not know about the linking of physical and human networks

A number of general research challenges in Network Science were set out in the National Research Council report in 2005 [1], based on a survey of academic institutions from which they learned;

...developing predictive models of the behavior of large, complex networks is difficult. There are relatively few rigorous results to describe the scaling of their behaviors with increasing size. Surprisingly, this is true for common engineered networks like the Internet as well as for social and biological networks.

Here we modify the committee’s broadly based research challenges and realign them with the purposes of the physical-human networks addressed in this proposal.

- *Dynamics, spatial location, and information propagation in networks.* The structure-function relation long identified as a fundamental problem in biology defines one of the basic challenges for networks arising in the physical and human domains. For example the statistics of information packets on complex networks do not have Poisson statistics but are clustered in time, occurring in bursts, requiring distributions with heavy tails. But the dynamics of such distributions are only partially understood and require further development [viii].
- *Modeling and analysis of very large networks.* Tools, abstractions, and approximations do not exist that allow reasoning about large-scale networks. Techniques that have modeled noisy and incomplete data in physical networks need to be extended to human networks.
- *Design and synthesis of networks.* With one or two exceptions, techniques are not available to design or modify a network to obtain desired properties of complex dynamic

³ The acronym HOT, originally short for *Highly Optimized Tolerance* has subsequently been used to mean *Heavily Organized Tradeoffs* and *Heuristically Optimized Tolerance*, and now it is used for any of a number of interchanges of the three words.

networks, particularly when multiple conflicting constraints must be satisfied as in CANs or NoN.

- *Increasing the level of rigor and mathematical structure.* A survey of the university campuses in the United States revealed a consensus that the state of the art in network science does not have an appropriately rigorous mathematical basis.
- *Abstracting the common concepts across fields.* A set of common concepts for network science does not exist that is defined across the various scientific disciplines. There is discipline-specific nomenclature that has been developed for specialized needs, but the equivalence of these terminologies for a discipline-independent characterization of networks has not been established.
- *Better experiments and measurements of network structure.* There is only a limited set of tools available for investigating the structure and function of large-scale networks, in part, because of the paucity of current data sets.
- *Robustness and security of networks.* There is a lack of understanding of networked systems and no design methodology that is both robust to variations in the components and secure against hostile intent.
- *Decision making in an information rich environment.* There is a lack of understanding in the relationship between the network structures and complexity, and the impact of this on organizational design and individual/unit behaviors.

2.4 Documenting successes

The development of a new science like Network Science, out of the many divergent fields of mathematics, physics, computer science, biology, psychology, and others, is fraught with difficulties. Scientists are expert critics, capable of rapidly detecting flaws in others' theories and methods, and unforgiving of theoretical and empirical shortcomings. These obstacles to successful collaboration and how they are overcome can provide instructive lessons learned for future multidisciplinary efforts. However, developing Network Science within this ASO can be a model for future joint and multidisciplinary efforts.

Science and engineering now routinely occurs in distributed "collaboratories." The possibilities for a substantial distributed research enterprise have been raised by the Board on Army Science and Technology (BAST) in considering a proposed Network Science, Technology and Experimentation Center (NSTEC). This Center would bring together a broad array of already existing research activities, either through expensive collocation or through using the emerging collaborative concepts to create a geographically distributed organization. This ASO can be seen as a forerunner to this much larger research enterprise to come.

The opportunities for a collaboratory are rich. But as a recent article shows, "distance matters" [ix]; where these matters have been studied in the world of science and engineering in great detail. The Science of Collaboratories (SOC) project created a data base of more than 200 existing collaboratories. Generalizations extracted from these data about factors that affect the success or failure of such projects will be used to structure the record of this ASO's efforts at collaboration in meetings, sharing of emails and documents, workshops, and products. In particular, this project will archive the growth of shared terminologies about network science, and formulate an extensive shared ontology of Network Science. This is one of the tasks proposed herein.

3. Research Plan

To dominate in a networked environment, the United States and allied nations must recognize the complex relationships within and among communications and information technologies, as well as the corresponding communications, information and social networks. These networks can be thought of as CANs, defined as a “dynamic network of many agents which may represent intelligent systems, individuals, groups, and units acting in parallel, acting and reacting to other agents” [x]. Understanding the behavior of a CAN is important not only for the Army’s defense transformation, but to understand the nature of asymmetric threats. Warfare must be analyzed as a complex network that is linked and interactive with the surrounding social-economic and political context. Complex networks share four properties: emergence, nonlinearity, uncertainty and adaptation. Essentially, these networks grow and evolve in unanticipated ways, they operate in a unique fashion that is not orderly, changing in spurts or in small numbers and they adapt to their surroundings and to their own changing behavior. Army scientists at ARL must understand the interplay of these four features of complex networks to develop NCW behavioral and organizational decision-making strategies.

Though NCW is dependent upon physical, information and communication networks, it is fundamentally about human and organizational behavior, and requires a new way of thinking about military operations [xi]. The Army currently has limited investment in network research in the cognitive and social domains of NCO, specifically in decision-making in an information-rich environment. This gap is addressed by the following proposed research.

We propose to develop the basic research foundation of a science of networks supporting the linkage between the physical and human (cognitive and social) domains as they relate to human decision making within the Army’s command and control structure. The strategy we adopt has three principle components: theory, computation/simulation and experiment/observation. In the theory component we propose to extend the most recent methods of statistical physics to non-stationary, renewal stochastic processes that appear to be characteristic of the interactions among nodes in complex networks. Another area of theory we propose to pursue is the phenomenon of synchronization, whose mathematical formulation has recently provided insight into how complex networks reach accommodation and cooperation. The theoretical analyses of complex networks, although mathematically rigorous, often elude analytic solutions and require large-scale simulation and computation to analyze the underlying dynamic process. We propose using agent-based modeling to simulate the dynamics of such complex networks, particularly models of dynamic decision-making under conflicting constraints and with incomplete information. In addition, we propose to develop decision-making scenarios from which to extract large amounts of data for analysis, for the development of theoretical models and the construction of large-scale computer simulations, as well as, optimal data processing technique to guide the theoretical analysis. We expect that the theory, computation/simulation and experiment/observation components will inform and refine one another in an iterative way through intense collaboration.

3.1 Technical Area 1: Network Theory

Overview: One of the mysteries of human social interaction is how agreements are reached and cooperative alliances are made. At the end of the nineteenth century the separation of phenomena into simple and complex was relatively straightforward. A simple network was one that could be described by one or a few variables, and whose equations of motion could be given, for example, by Newton's laws. In such networks the initial conditions are specified and the final state is calculated (predicted) by solving the equations of motion. The predicted behavior of the network, typically a particle trajectory, is then compared with the result of experiment and if the two agree, within a pre-established degree of accuracy, the conclusion is

that the simple model provides a faithful description of the phenomenon. Thus, simple physical networks have simple descriptions. Note that we do not choose to bring up nonlinear dynamics and chaos here, since these concepts did not influence the nineteenth century scientists applying physics to the understanding of society. However, we find that the modern understanding of complex networks does require the use of these techniques.

As more elements are added to a network there are more and more interactions, and the relative importance of any single interaction diminishes proportionately. There comes a point at which the properties of the network are no longer determined by the individual trajectories, but only by the averages over a large number of such trajectories. This is how the statistical picture of a phenomenon replaced the individual trajectory description. The erratic single trajectory is replaced with a distribution function that describes an ensemble of trajectories and the equations of motion for individual elements are replaced with an equation of motion for the probability distribution function.

Individuals become part of a ‘mob’ or a social group in a number of ways: choice, peer pressure and subliminal seduction; but always through a sequence of decisions, either conscious or not. The mathematical modeling of cooperative behavior between and among CANs is often found in the context of synchronization [xii] frequently seen as the manner in which order emerges from chaos. Biological oscillators such as pacemaker cells in the human heart are notoriously poor clocks, which is to say, that the firing period varies from cell to cell and from firing to firing. However, collections of such naturally variable entities when allowed to interact become phase locked and lose their individual variability. How natural phenomena accomplish this phase synchronization has been gaining increasing attention since Turing's early work on the modeling of collective phenomena and informs the discussion on how social organizations achieve consensus. The more recent mathematical investigations into the coupling mechanisms of such collectives was made by Kuramoto [xiii] using a network of coupled nonlinear oscillators to mimic natural synchronization in oscillating chemical reactions. A similar strategy was employed by Winfree [xiv] in his study of cardiac oscillations.

Multiple-scales and across-scale coupling are recurrent themes in the study of complex networks. Fractal geometry was invented to describe the quantitative aspects of phenomena with multiple scales (no characteristic scale), but what is needed now is a way to describe the dynamics of such complex phenomena/networks. Network characteristics cannot be deduced from the properties of individual components; they must emerge during the formation and growth of the network. Consequently we need mathematics to quantify the strength of the interactions between the network components, as well as to describe how a network develops in time and responds to perturbations (excitations). One technique that may be useful in this regard is the fractional calculus [8], where the differential equations of motion used in traditional physics are replaced by fractional equations of motion.

Project 1-1: Complexity theory and modeling without scales

Technical Objectives: Provide understanding of how to build a network. The complex adaptive systems and complex adaptive network approaches have been increasingly used in organizational studies. Yet, leadership research has barely begun to use this paradigmatic lens. Given the limitations of traditional leadership theory and the increasing emphasis on organizational adaptation in asymmetric environments, the complex network approach has potential for providing reasonable gains in leadership research. This research will be inclusive of technological use for gaining information supremacy while incorporating human-in-the-loop effects to achieve human network integration.

Technical Approach: Create theory, explore the use of computational models and conduct empirical studies that address the complex network approach to understanding leadership. Empirical studies will be conducted at tactical and operational venues in connection

with Technical Area 3, while computational models designed to test the theory are proposed in Technical Area 2.

Ubiquitous aspects of complex networks are the appearance of non-stationary, non-ergodic, and renewal statistical processes. These properties are manifest through inverse power-law statistical distributions that not only challenge traditional understanding of complexity in physical networks, but require new strategies for understanding how information is exchanged between networks, as in the case of interest here between physical and human networks. The approach proposed herein is to adapt the methods of non-equilibrium statistical physics that have been used to characterize the dynamics of complex phenomena and extended to the study of such social phenomena as linguistics, biofeedback techniques and the brain's response to music [xv] and to further develop them to model decision-making with incomplete information in an uncertain environment.

A decision maker does not have in mind all possible outcomes, even though that is presented to be the case by positing an 'optimal' strategy. In reality a decision maker is constrained to satisfy a minimum requirement, that being to do the best possible under a given set of constraints or with a given amount of information. This information processing constraint causes problems similar to those arising from time constraints, since an optimal decision is constrained by the time available to make it. Consequently a key issue is to understand the way information is received, assimilated and used, all of which depend on its space-time form.

In order to understand how information is transferred among complex networks such as required in the decision-making process we investigate the phenomenon of memory and examine the influence of memory on stochastic processes. Moreover, we propose to examine how random phenomena with memory require a description using a fractional stochastic differential equations (FSDE) in which the memory kernel is interpreted as a fractional operator to establish a correspondence with an increasing literature on the application and interpretation of the fractional calculus to the description of complex dynamic phenomena [8]. Note that the FSDE only arise when the microscopic time scales diverge and consequently overlap with the macroscopic time scales, which is to say, there is no time scale separation across the dynamics. The overlapping time scales of the changing environment of the battle field (here this is the micro-scale) and those of decision-making (here this is the macro-scale) strongly suggest the need for such a real time stochastic model.

We propose the further development of fractional equation methods for application in the physical and human networks as well as in their coupling.

Project 1-2: Information propagation in complex adaptive networks

Technical Objectives: Develop methods to quantify, design and control the fractal statistics of information transfer in complex adaptive communication networks.

Technical Approach: A perennial problem in the physics of communications is matching information flow to the physical structure of the channel supporting that flow in such a way as to maximize efficiency, that is, maximize the information transferred within the channel. For the purposes of this proposal it is useful to replace the notion of channel with that of network in order to avoid unnecessary confusion. To understand the dynamics of complex networks the traditional analysis of information flow and network traffic, involving exponential distributions of messages and consequently Poisson statistics of traffic volume, is abandoned.

The investigation into information propagation proposed here is distinct from what has been done in the past in that we do not use the information entropy of Shannon, nor the control theory of Wiener, but rather we propose to address questions of spatial heterogeneity and temporal non-stationarity of dynamic complex networks that were almost universally ignored in the past; recognizing that traffic, whether on the Internet or in the brain, is not statistically uniform, but occurs in bursts in both space and time and links are not homogeneous but vary in quality. We propose to understand the influence of long-time memory, often called non-Markov

behavior, or heavy-tailed distributions, on packets in complex communication networks, and their impact on information measures, such as those developed using scenarios in Technical Area 3.

The modern mathematical representations of time keeping network nodes are often chaotic attractors, that are periodic, but not harmonic, for example, the Rössler oscillator has been used to represent the output of a single neuron [xvi]. Wood et al [xvii] have shown that coupled stochastic clocks can manifest cooperative, that is to say, synchronized behavior. Varela et al [xviii] postulate that brain function, such as cognition, rests on the cooperative behavior of collections of many neurons. The strategy of Bianco et al. [xix] is to map brain activity onto networks and consequently study the dynamics of the collections of neurons modeled as such networks. Changes are found in the topology of the network that describes the brain activity as driven by a non-Poisson renewal (NPR) process operating in the non-ergodic regime. Moreover, a collection of blinking quantum dots has the same dynamical behavior as brain activity [xx], and so Bianco et al. [18] postulate that the two complex networks may share a dynamic model. We propose to further extend this analysis to a cognitive model of decision-making through the exchange of information between two or more complex networks in conjunction with Technical Area 3. This is part of the search for common dynamic features among complex networks in various disciplines.

Project 1-3: Network Stability and Decision Agility

Technical Objectives: Networks are becoming critical to military missions; this requires a mission-centric awareness that enables critical insight of network functioning for decision makers. This task proposes examining and describing the conceptual relationships between information networks and the social networks that utilize them, as well as the impact on decision-making in this networked environment.

Technical Approach: Among other techniques we propose to employ the Missions and Means Framework to analyze network models "without scales" and "with rich scales", which requires the application of the state of the art network theory to military configurations. Moreover to modify and adapt the hierarchical Military Decision Making Process (MDMP) doctrine in light of high speed peer to peer communications that the warfighter internet enables, and which accounts for intrinsic trade-offs between network stability/instability and decision agility/rigidity. We propose to develop general principles that describe the dynamics of a network related to a specific mission, such as traffic and the underlying topology, including the definition of the appropriate quantities and measures to capture how these variables contribute to the formation of decision-making in complex networks.

The adaptive control of thought-rational (ACT-R) has been a leading contributor to advances in cognitive science within the Army and is intended to be a unified theory of the workings of the majority of cognitive processes. We propose to build an ACT-R model from data collection and subject matter expert (SME) guidance on detailed tasks, sequences of events, goals, cues, visual displays, communications, and synchronized tasks. The goal is to build a model of cognitive networks that can be used in the evaluation of human decision-making. This will be done in close collaboration with the scenarios developed in Technical Area 3 and the theory developed in Technical Area 1.

3.2 Technical Area 2: Network Simulation and Computation

Overview: Decision-making is the process of choosing among alternative courses of action for the purpose of attaining a goal or goals. Such decisions are made in the context of models, a simplified representation (abstraction) of reality, because reality is too complex to copy exactly. Moreover, much of the complexity encountered is *irrelevant* in problem solving, but the trick is knowing what can and what cannot be ignored.

When a group comes together to pursue a goal or make a decision, how should they interact; how should the decision be made? There is no best answer to these questions and experience shows that the group should adapt the answer to fit the context of the question. One systematic approach to solving this problem is by using a computer-based multi-agent system (MAS), which is a collection of distributed software programs called *agents*. These programs interact to achieve a goal, sense the environment, and plan a variety of actions either proactively or reactively given an inferred environment state and a set of goals. Moreover an *agent* can execute actions to change the environment. As pointed out by Barber et al. [xxi] organization decision-making using MAS examines the individual agent- and system-level behavior of interacting software agents.

We propose to adopt this computer-based strategy for the construction of dynamic decision-making models to military command and control with an emphasis on the complex network structure in NCW. There are a number of strategies that can be explored in the exercise of MAS including: 1) individual agents who do not make decisions but obey orders from a master agent; 2) agents are team members and decision-making responsibility is shared and 3) an agent has local autonomy for decision making. These various decision-making modes for a given network architecture can provide insight into how to most efficiently implement NCW into the future combat system.

In 1963 Arrow [xxii] showed that there are five desired properties for a situation-independent group decision-making organization and then went on to prove that an organization can only have three of the five properties without encountering an inconsistency. These properties are:

- *Consistency*—Individual complete, transitive, and reflexive orderings of preferences should result in a group preference ordering with the same properties.
- *Unanimity or Pareto Requirement*—If all agents agree on a preference, the group decision should reflect that preference.
- *Unrestricted Domain*—No options should be arbitrarily excluded.
- *Ignoring Irrelevant Attributes*—The ordering outcome of a decision process preferring A to B should not change if a third option is introduced.
- *Absence of Dictators*—No agent should always be able to completely control the outcome of the decision-making process through its decisions.

Arrow's *Impossibility Theorem* established that collective rationality, the concept that a decision making group can itself behave rationally, is meaningless [xxiii]. However, as Barber et al. point out in [xxiv] this is the ideal situation and the ideal is often compromised in the real world and consequently Arrow's Impossibility Theorem is interpreted in the present context such that a MAS designer must make engineering tradeoffs when choosing a decision-making framework for a situation.

Project 2-1: Network optimization under conflicting constraints

Technical Objectives: Develop algorithms for robust local/global optimization of network metrics.

Technical Approach: Large-scale data processing is a generic problem in today's military. Here we are concerned with that aspect of data processing that can reveal patterns in time series measured in linked physical and human complex networks. One application is the calculation of measures for the quality of performance of individuals or of the network. Such measures might include minimizing the difference between best and worst performance in individual or network-level (minimizing variability); maximizing best-case agent or network-level performance; minimizing worst-case agent or network-level performance. In particular, we propose to focus on analyzing the cognitive measures of performance being developed in Technical Area 3 and examine the impact of optimizing on social/cognitive measures rather than traditional network performance metrics. We also propose to leverage the work being done in

Technical Areas 1 and 3 on the intrinsic trade-offs between network stability/instability and decision agility/rigidity.

In many large-scale networks the nonlinear subnetworks have access to local information and must make local decisions, that is, they are locally optimized. Such subnetworks must still work together with other subnetworks to achieve a common network-wide goal, that is, global optimization. Each subnetwork operates with limited knowledge of the structure of the overall network, and the global and local optimizations may be at odds with one another. We propose to develop the mathematics of such global optimization under conditions of conflicting constraints imposed by the dynamical subsystems. The mathematical/computational challenge is to recognize control networks as collections of physical and information networks, with intricate interconnections and interactions. Controllers are required to be robust with respect to modeling uncertainty and to adapt to slow changes in the network dynamics. We propose to generalize control theory through the mimicking of self-repair and replication found in biological networks.

Deliverables: The publication of research papers in the top peer reviewed technical journals, the presentation of results at national and international forums and the transfer of the technical information to the appropriate Army laboratories.

Project 2-2: Mission-based Integrated Modeling and Simulation

Technical Objectives: Define requirements for models and simulations to represent the integrated network (human, propagation, hardware, and software) performance and priorities as mission evolution requires task-organization and task re-organization to change, based on operational necessity. Outputs would be 1) an agent-based simulation which integrates human, propagation, hardware, and software into a task-based assessment of mission performance and 2) a quantitative assessment of the complex trade space.

Technical Approach: An agent-based simulation will be used to study the dynamics of a representative suite of integrated network exemplars. To build these simulations, we propose to use the Complex Reactive Behavior Combat Agent Model (CoRBCAM), an agent-based modeling and simulation toolset that evolved from research conducted under two ARL Director's Research Initiative (DRI) awards [xxv], [xxvi]. CoRBCAM simulates the combat interactions of two or more adversarial units of tactical battle space entities via employment of a complex variety of reactive behaviors [xxvii]. Such behaviors reflect the execution of pre-defined military tasks in a manner consistent with the military Missions and Means Framework (MMF) [xxviii]. Through the use of novel visual programming technology, CoRBCAM allows a user to construct task-oriented behaviors that are executed by tactical combat agents (i.e., simulation agents representing military platforms and infantry) during the course of a simulation. Given that a generic combat agent may be defined with any number and variety of reactive behaviors, CoRBCAM can simulate the decision-making processes (DMPs) associated with human soldiers, hardware objects, and software objects via assignment of corresponding behaviors to an unlimited set of agents.

We propose to recursively execute the following sequence of project tasks:

First, an instance from a suite of representative integrated network exemplars will be defined in terms of i) the mission context associated with the tactical nodes making up the integrated network operating within a notional battle space, ii) network node types (e.g., manned ground vehicle, unmanned aerial vehicle, unmanned ground sensor, infantryman with wireless digital radio, etc.), iii) the set of mission-related tasks assigned to each node within the network, iv) the set of fully-functional and degraded capabilities of a node that it will utilize to execute its tasks (e.g., digital communication, reduced range visual sensing, maximum velocity reduced by 50%, etc.), and v) the set of Boolean "fault trees" that define how the function (or dysfunction) of hardware, software, and/or human components within a node maps to fully-functional and degraded capabilities resident within the node.

Next, the tasks assigned to each node within the integrated network instance will be converted to combat agent behaviors within a CoRBCAM simulation. These agent behaviors will be designed to facilitate autonomous behavior modification by combat agents as a function of their current degraded capability state. This capability-based behavior modification represents dynamic context awareness within agents as they continue to operate within the simulated battle space [xxix]. These assignments will be done in close collaborations with projects in Technical Area 3.

Then, an operational terrain representation (e.g., open fractal field, urban landscape) will be constructed for the battle space within which the integrated network exemplar will be simulated.

Next, CoRBCAM simulations of the integrated network exemplar will be run (using the previously configured battle space terrain and combat agent task-oriented behavior sets). These simulations will model inter-nodal data communication via simple first-order line-of-sight radio frequency (RF) signal propagation, with intermittent noise. Network state and MMF-compliant performance measures will be recorded as time series outputs during the course of a CoRBCAM simulation run.

Finally, we propose to analyze the time series results gathered from the CoRBCAM integrated network simulations using techniques gathered from state of the art time series analysis, statistical-mechanics-oriented network analysis [xxx], Formal Concept Analysis [xxxi], and recurrence plot analysis [xxxii]. Analysis of these data will serve to characterize the distribution of plausible operational outcomes by revealing emergent behaviors demonstrated through the integrated network exemplar during CoRBCAM simulations.

By comparative analysis of all integrated network exemplars within the exemplar suite, we propose to quantitatively assess the complex trade space governing integrated network design and deployment. The data generated under these exemplars will also serve as input to the network theory being developed in Technical Area 1 to assess the effectiveness of new and previously existing statistical measures of dynamic complex networks.

Deliverables: The publication of research papers in the top peer reviewed technical journals, the presentation of results at national and international forums and the transfer of the technical information to the appropriate Army laboratories.

3.3 Technical Area 3: Network Experimentation/Observation

Overview: The relationship between network structure and complexity is of critical importance in defining mission-centric organizational design and supporting individual/unit behaviors. These conditions are the *sine qua non* to effective decision making in a networked environment. While the physical and information aspects of NCO are moderately well understood, the fundamental problems of NCO lie in the social domain [1]. Questions that we must seek answers to include:

- How do people interact with technology to develop shared understanding and subsequently make decisions that are fundamentally better than what we can do today?
- What exactly is shared understanding? How would we recognize it if we observed it? What are the necessary parameters to ‘sharing’? With whom should someone share? How would these sharing protocols be developed? What are the technological requirements for supporting this advancement in decision making?
- How does the uncertainty or incomplete knowledge influence decision making?

- When operating over a dynamic geographical, temporal, and political space, how can we organize very large groups of people to prosecute the many tasks that must be synchronized for a military operation to succeed?

Decision-making in CANs is challenging due to the interacting properties of these systems: emergence, nonlinearity, uncertainty and adaptation. It is no longer sufficient to study the impact of uncertainty on decision processes; rather we must take into account the multi-factorial nature of the network on intended and unintended consequences. There are many avenues of research that could produce beneficial findings to this problem. One valid approach would focus on the explicit and implicit influences of networked nodes on decision making behavior. This ‘social contagion’ effect has impact for networked decision making [1].

The proposed approach is to explore decision making in an information-rich military environment through field experimentation to assess how decision makers adapt processes for information search, and how these searches produce knowledge that drives decisions. This would help us understand the impact of incremental increases in information on the search and decision processes. This approach is intended to provide the necessary data to produce models and simulations and to support theory development. We propose to support experiment by the development of scenarios that explicate processes, organization, and technologies required to conduct a mission. The goal of scenario building is to enable the emerging Network-enabled Force to conduct Mission-driven Decision-centric Operations, and to enable Decision-centric Operations to task-organize (and re-task-organize) constrained Network capabilities (finite wireless bandwidth, finite human cognition) based on dynamic mission priorities. This approach is predicated upon the integration of the representation of human factors with the representation of technology to provide holistic assessment. This approach will combine task-based assessment of soldier/unit performance with technology-based assessment of materiel to provide a rigorous analytical methodology to improve assessment of Network enabled capabilities across the echelons of mission, task, organizational, and materiel hierarchies.

Project 3-1: Scenario Building and Testing

Technical Objectives: Develop a formal procedure that maps operational analysis onto network analysis along with methods to test the sensitivity of the quality/quantity of shared information, the proper distribution of information, and its net effect on the mission performance in the computational scenarios developed in Technical Area 2.

Technical Approach: Build a scenario to analyze the sensitivity of the quality/quantity of shared information, the proper distribution of information, and its net effect on the mission performance in that scenario. Part of the reason for scenario-based exploration is to develop techniques for collaborating across disciplines represented in the ASO.

Employ the ‘Missions and Means Framework’ to conduct the mission analysis to extract the heuristics and patterns of the combined human/materiel networks. Incorporate these extracted heuristics and patterns into the network theory tasks of Technical Area 1 and network simulation tasks of Technical Area 2. We propose that the mission analysis separate circumstances where "big pipes" (either land-line and/or satellite) can provide bandwidth in excess from the power-limited/bandwidth-limited tactical land warfare environment.

We propose to develop a formal procedure to map the operational analysis to the equivalent network analysis. This entails restating the operational steps: 1) statement of mission; 2) collection of information; 3) establishing alternatives; 4) evaluating alternatives and 5) optimize for final decision. The operational analysis constitutes a linear sequential approach to decision-making, which we propose to transform into a networked approach that is nonlinear, parallel and which terminates when a solution is found such that the cost of further searching exceeds the expected benefits of doing so. This technique is neither optimal nor suboptimal, but constitutes a different way of making decisions, which in economics is called *satisficing* [xxxiii].

Project 3-2: Understanding the network effects on decision making

Technical Objectives: It is no longer sufficient to study the impact of uncertainty on decision processes; rather we must take into account the multi-factorial nature of the network on intended and unintended consequences. This effort proposes to expand the initial work conducted over the past several years on the impact of uncertainty on decision making, and integrate the characteristics of nonlinearity, adaptation, and network emergence on decision makers.

Technical Approach: Decision-making in dynamic complex networks is challenging due to the interacting properties of these networks. Consequently, any theory of decision-making must include, but is not be limited to, the qualities of emergence, nonlinearity, uncertainty and adaptation. There are many avenues of research that could uncover the influence of network interactions on decision-making; the approach proposed here is to focus on the explicit and implicit influences of networked nodes on decision-making behavior. This ‘social contagion’ effect has impact for networked decision-making.

Social contagion includes wide spread effects, such as the wave of suicides that swept across Europe two centuries ago and attributed to Goethe’s tragic tale of suicide “The Sorrows of Young Werther”. Today the study of influence between and among such events and those less dramatic is done in a more systematic way. Herein we propose examining social contagion using ideas from synchronization theory developed in Technical Area 1 using the C3TRACE modeling architecture to conduct this task, and develop data for the model from the “C4ISR On The Move Experiment” conducted annually at Ft. Dix, NJ.

Deliverables: The publication of research papers in the top peer reviewed technical journals, the presentation of results at national and international forums and the transfer of the technical information to the appropriate Army laboratories.

Project 3-3: Measures of human performance in networked operations

Technical Objectives: As systems of systems are networked on the modern battlefield to form networks or networks, analysts cannot continue to treat soldiers as groups of individuals operating in this CAN. We must develop network-level metrics to account for group dynamics that address shared understanding, the concept of self-synchronization (or group synchronization), and decision superiority that is expected to result from these pre-conditions. As modeling and simulation grow in importance in test and evaluation, we need cognitive metrics that can be deemed robust and reproducible and that can be evaluated in field and laboratory experiments.

Technical Approach: Through the annual “C4ISR On The Move Campaign of Experimentation” (Ft. Dix, NJ), we propose to develop and test cognitive metrics that can be used in field and in modeling and simulation experiments. These metrics will be developed in collaboration with the tasks in Technical Areas 1 and 2. Moreover, we propose to test the metrics in field experiments that employ networked communications architecture and incorporate information from manned and unmanned networks. The contributions that unmanned networks make to shared understanding must be captured to allow for the future development and deployment of these networks. For example, measures of how many unattended ground sensors are required for a platoon-sized element will be developed. If these sensors are not deployed carefully, the images they send to the operator may be misinterpreted and conditions of information overload may develop (e.g., is there one truck approaching or three). In the networked environment, the workload concept needs to be re-evaluated. In addition, we must determine if mental effort and frustration can overtake physical fatigue in the overloaded workload condition. Also, we propose to construct measures of the goodness of the network from the human perspective.

Deliverables: The publication of research papers in the top peer reviewed technical journals, the presentation of results at national and international forums and the transfer of the technical information to the appropriate Army laboratories.

3.4 Technical Area 4: Workshops and Historical Record

Objectives: To maximize the collaboration among the scientists from the various disciplines within ARL in achieving their research goals under the three technical areas above. Moreover we propose to maintain a historical record of the social/technical interactions, along with documentation of the successes and failures of collaborations in order to chronicle how to replicate the successes and avoid the failures in future programs.

Technical Approach: There will be monthly one-day working group meetings of all scientists participating in the ASO program, over and above the day-to-day collaborations, in order to maximize the information exchange and involvement of scientists across disciplines. The purpose of the monthly meetings is to develop an understanding between the research groups including a knowledge and understanding of the technical tools being used and developed in the research. To achieve this understanding there will be a formal technical presentation given by an ASO team member, on some aspect of the overall problem, at each meeting. The host sites and group leaders will rotate, each month; furthermore, this is to be a technical not an administrative meeting.

At the end of each fiscal year a workshop will be hosted focusing on what has been accomplished within the ASO program during that year and how that research relates to what is being done in the broader scientific community. The venue for the workshop will change from year to year. Ongoing collaborations will be actively promoted at these workshops, to foster information exchange among the ARL scientists, academics and industry laboratory researchers.

The opportunities for a collaboratory are rich. But as a recent article shows, “distance matters” [xxxiv]. These scientists have studied these matters in the world of science and engineering in great detail. The Science of Collaboratories (SOC) project created a data base of more than 200 existing collaboratories. Generalizations extracted from these data about factors that affect the success or failure of such projects will be used to structure a record of the ASO collaborations in meetings, sharing of emails and documents, workshops, and products. In particular, we propose to archive the growth of shared terminologies about network science, and formulate an extensive shared ontology of Network Science to be made available to the broader scientific community.

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Network Science for Human Decision-Making

13th International Command and Control Research Technology Symposium

ASO Committee:

Bruce J. West, PhD

Elizabeth K. Bowman, PhD

Brian Rivera, PhD

Bruce J. West

**Mathematical & Information Science
Army Research Office**

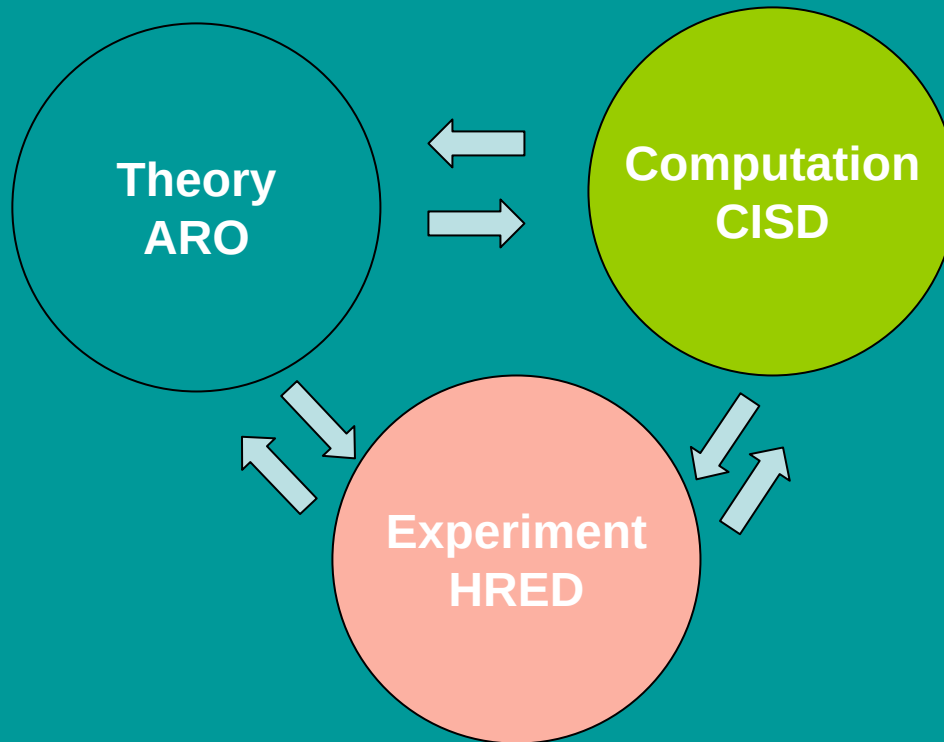
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- **First: What do we want to do?**
 - Determine how networks affect decision-making in NCW.
- **Second: How are we going to do it?**
 - Collaboration across disciplines and directorates
- **Third: What are we going to use?**
 - theory; experiment/observation; computation/simulation
- **Fourth: How are we going to know what works?**
 - archive interactions; regular meetings and workshops

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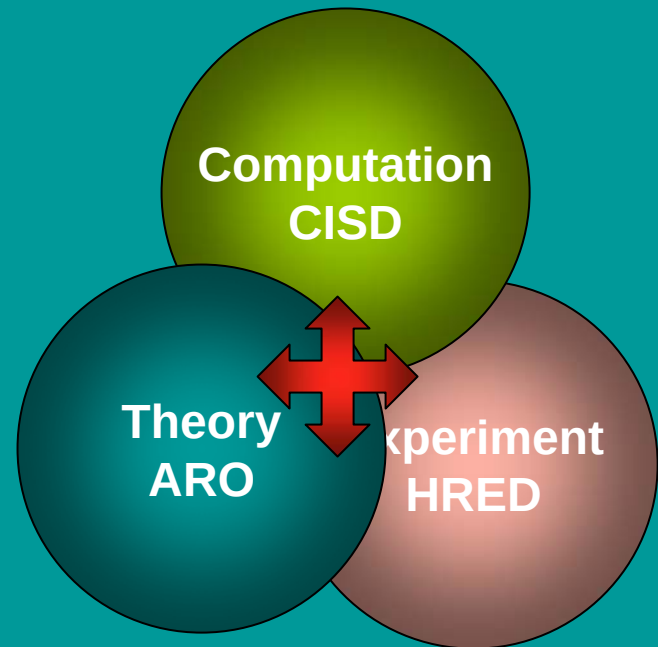
- What makes this proposal different?
 - mandatory collaboration across disciplines and Directorates
 - ARO, CISD, SLAD and HRED
 - PI from separate ARL Directorate for each technical area
 - ARO B.J. West
 - CISD B. Rivera
 - HRED D. Bassan
- Project itself is an experiment
 - historical record to monitor successes and failures of collaborations
 - summarize what works at yearly workshops
 - technology anthropologist records and evaluates group interactions

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Historical form of collaboration among and between disciplines and ARL Directorates.

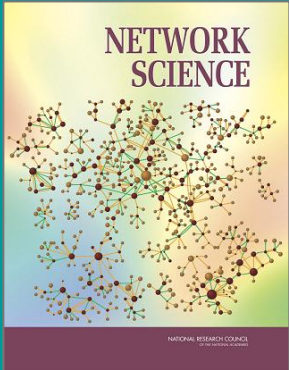
Proposed form of collaboration interleaves the various disciplines and ARL Directorates.



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- **Setting the stage for research projects**
 - **What constitutes a network?**
 - Structure to integrate component contributions
 - Who (what) interacts with whom (what)?
 - The Army
 - Social, cultural, and organizational processes that foster cooperation
 - Ants, bees and termites
 - **All networks are not equivalent.**
 - Node properties – can they learn, adapt; are they mobile..?
 - Link properties – what is being transferred (energy, information)?
 - Embeddedness – what other networks are connected?
 - What are the boundary conditions?
 - What are the constraints?

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Research Challenges related to decision-making

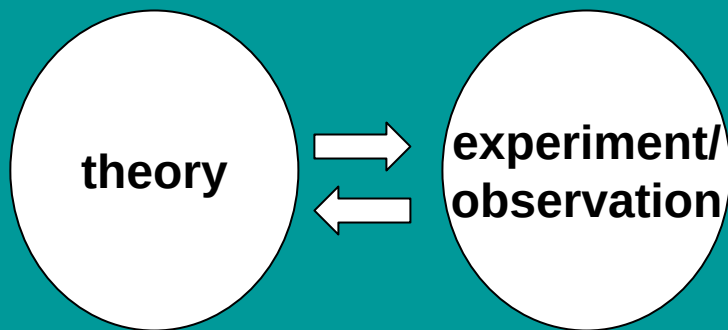
1. Dynamics, spatial location, and information propagation in networks
2. Modeling and analysis of very large networks
3. Design and synthesis of networks
4. Increasing the level of rigor and mathematical structure
5. Better experiments and measurements of network structure
6. Robustness and security of networks
7. Abstracting common concepts across fields

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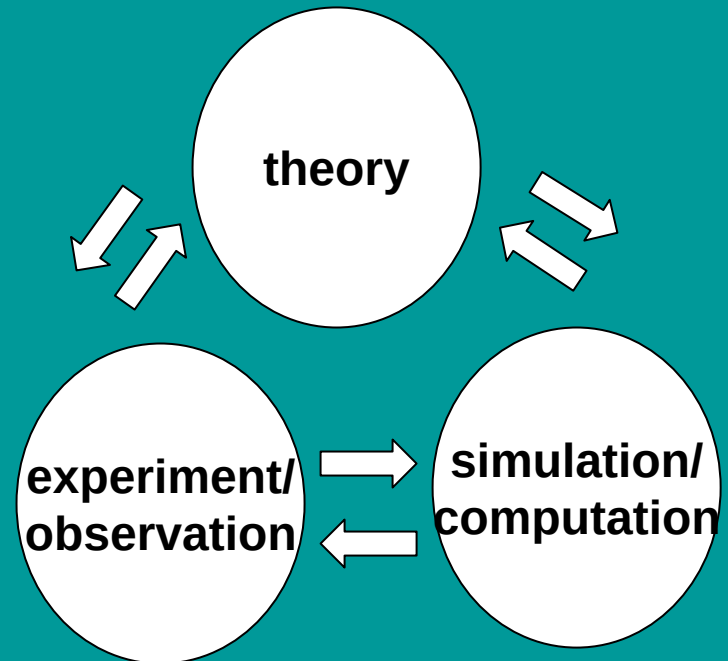
- **Technical Area 1: Network Theory (ARO)**
 - **Project 1.1: Complexity theory and modeling without scales (ARO and HRED)**
 - leadership research based on social networks
 - modeling uncertainty: non-stationary, non-ergodic renewal
 - information exchange between human and other networks
 - **Project 1.2: Information propagation in complex adaptive networks (ARO and CISD)**
 - match information flow between complex networks
 - synchronization of fluctuating elements
 - cognitive model of information dispersal
 - **Project 1.3: Network stability and decision agility (ARO and HRED)**
 - impact of network on decision-making
 - build model of cognitive network to evaluate decision-making

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- Topology of scientific method is fundamentally different



Two-tiered iterative process
TETETE...



Three-tiered iterative process
TCETCE... or TETCETC... or

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- **Technical Area 2: Network Simulation and Computation (CISD)**
 - **Project 2.1: Network Optimization under conflicting constraints (CISD, ARO and HRED)**
 - impact of cognitive measures of performance on network metrics
 - local (subnetwork) versus global (network) optimization constraints
 - generalize control theory to include self-repair
 - **Project 2.2: Mission-based integrated modeling and simulation (SLAD and HRED)**
 - agent-based simulations integrating human, propagation, hardware and software into task-based assessment of mission performance
 - simulate decision-making processes of soldiers, as well as, hardware and software objects
 - carry out a variety of detailed scenarios analyzing task completion within the network

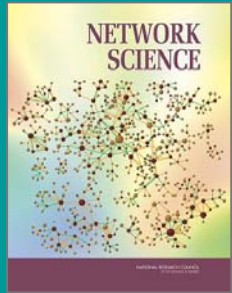
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- **Technical Area 3: Network Experimentation/Observation (HRED)**
 - **Project 3.1: Scenario building and testing (HRED and ARO)**
 - map operational analysis into network analysis
 - explore sensitivity to shared information
 - **Project 3.2; Understanding the network effects of decision-making (HRED and ARO)**
 - extend analysis of influence of uncertainty on decision-making
 - integrate characteristics of nonlinearity, adaptation and network emergence on decision makers
 - **Project 3.3: Measures of human performance in networked operations (HRED, CISD and ARO)**
 - develop metrics for network-of-networks; shared understanding and group synchronization
 - information dispersal from manned and unmanned networks
 - effect of mental effort and frustration compared with physical fatigue on decision-making

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- **Technical Area 4: Workshops and Historical Records**
 - maintain record of social/technical interactions
 - maintain record of successful and failed collaborations
 - organize and document monthly technical one-day meetings
 - Set agenda
 - guest speaker
 - focus on specific problem areas
 - mandatory attendance
 - organize and document annual 2-3 day workshop
 - review successes, dead ends, re-organize, re-orient and re-determine the state-of-the-art in decision-making
 - mandatory attendance
 - achieve growth of shared terminology for network science

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Areas of Military Value related to decision-making

1. Modeling, simulating, testing and prototyping very large nets
2. Command and control of joint/combined networked forces
3. Impact of network structure on organizational behavior
4. Security and information assurance of networks
5. Relationship of network structure to scalability and reliability
6. Managing network complexity
7. Improving shared situational awareness of networked elements
8. Enhanced network-centric mission effectiveness
9. Advanced network-based sensor fusion
10. Hunter-prey relationships
11. Swarming behavior
12. Metabolic and gene expression networks