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TECHNICAL REPORT

Integrated Adversarial Network Theory (iANT)

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July 2011

HDTRA1-08-1-0002

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14. ABSTRACT

As the BAA for this grant noted, social network studies have proliferated in recent years but there has been a significant lack of integration across network studies such that "a broad, generic, adaptable, flexible, and modular theory of social networks… has not been realized" (DTRA BAA). This is a summary report of a 3-year basic research grant whose overarching objective has been the development of just such an integrated social network theory. It is important to emphasize at the outset that this project was not an empirical one and did not involve data collection, nor were any theories submitted to empirical test. In focusing on the generation of integrated network theory, our focus has been exclusively theoretical. The results of our work have been published in a number of peer-reviewed journals (e.g., *Science*, 2009—see Appendix A for a detailed list).

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CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ——→ BY ——→ TO GET
TO GET ←—— BY ←—— DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	$meter^2$ (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	t_k = ($t^{\circ}f$ + 459.67)/1.8	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	$meter^3$ (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/$inch^2$ (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/$foot^2$	4.788 026 x E -2	kilo pascal (kPa)
pound-force/$inch^2$ (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-$foot^2$ (moment of inertia)	4.214 011 x E -2	kilogram-$meter^2$ (kg-m^2)
pound-mass/$foot^3$	1.601 846 x E +1	kilogram-$meter^3$ (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

Integrated Adversarial Network Theory (iANT)

Final Report

HDTRA1–08–1-0002-P00002

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The report pulls together material drawn from a number of papers and presentations by the authors on this topic.

Acronyms Used in the This Report

Acronym	Description
GPI	*Graph-theoretic Power Index*. A metric developed by Markovsky, Willer and Patton to measure potential power of each node in a network, based on their position.
OOP	*Object Oriented Programming*. A key principle of OOP is that one should program to an interface rather than an implementation. What this means is that higher level code shouldnot have to know the details of how lower level code works.
SH	*Structural Hole Theory*. This theory argues that the value of a network is less a function of the strength of ties that make it up than it is of the structure of those ties. Networks that are rich in structural holes (i.e., one's contacts tend to lack direct connections with each other) are more efficient instruments for the collection and control of novel information (Burt, 1992).
SNA	*Social Network Analysis*. The field of research that studies social networks.
SWT	*Strength of Weak Ties*. This theory argues, somewhat counter-intuitively, that it is one's weak interpersonal ties (rather than one's strong ties) that are most likely to be the source of novel information (Granovetter, 1973).

1. Introduction

As the BAA for this grant noted, social network studies have proliferated in recent years but there has been a significant lack of integration across network studies such that "a broad, generic, adaptable, flexible, and modular theory of social networks… has not been realized" (DTRA BAA). This is a summary report of a 3-year basic research grant whose overarching objective has been the development of just such an integrated social network theory. It is important to emphasize at the outset that this project was not an empirical one and did not involve data collection, nor were any theories submitted to empirical test. In focusing on the generation of integrated network theory, our focus has been exclusively theoretical. The results of our work have been published in a number of peer-reviewed journals (e.g., *Science*, 2009—see Appendix A for a detailed list). It is hoped that the eventual payoff will be the fruitful application of this integrated network theory to a range of scenarios relevant to homeland defense, ranging from the proliferation of weapons of mass destruction to the disruption of terrorist cells.

2. Project Goals

Social network analysis (SNA) is currently popular. As shown in Figure 1, publications referencing "social networks" have been increasing exponentially over time. The interest in networks spans all of the social sciences, and is rising even faster in physics, epidemiology and biology. Table 1 shows the prevalence of social network analysis publications across multiple fields and Figure 2 shows the citation patterns among the top 500 cited social network analysis articles. In management research, social networks have been used to understand job performance (Sparrowe, Liden, Wayne and Kraimer 2001), turnover (Kilduff and Krackhardt 1994; Krackhardt and Porter 1985, 1986), promotion (Burt 1992), innovation (Obstfeld 2005), creativity (Burt 2004), and unethical behavior (Brass, Butterfield, and Skaggs 1998). And in management consulting, network analyses are fast becoming standard diagnostic and prescriptive tools (e.g., Anklam 2007; Baker 2000; Bonabeau and Krebs 2002; Cross, Parker and Borgatti 2000).

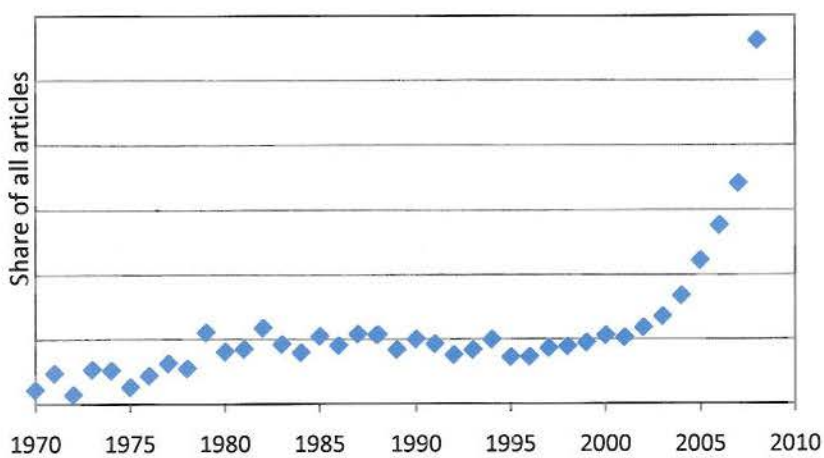

Figure 1: Share of all articles indexed in Google Scholar with "social network" in the title, by year.

Field	Publications	Pct all SNA
Sociology	1330	14.26%
Public, occupational health	862	9.25%
Management	581	6.23%
Psychiatry	438	4.70%
Anthropology	404	4.33%
All other business	381	4.09%
Geography	374	4.01%
Economics	366	3.93%
Psychology, multidisciplinary	364	3.90%
Gerontology	348	3.73%
OTHER (e.g., PHYSICS)	3876	41.57%
All	9324	100.00%

Table 1: Number of articles across fields with "social network" in the title, abstract, or keyword indexed in the Web of Science

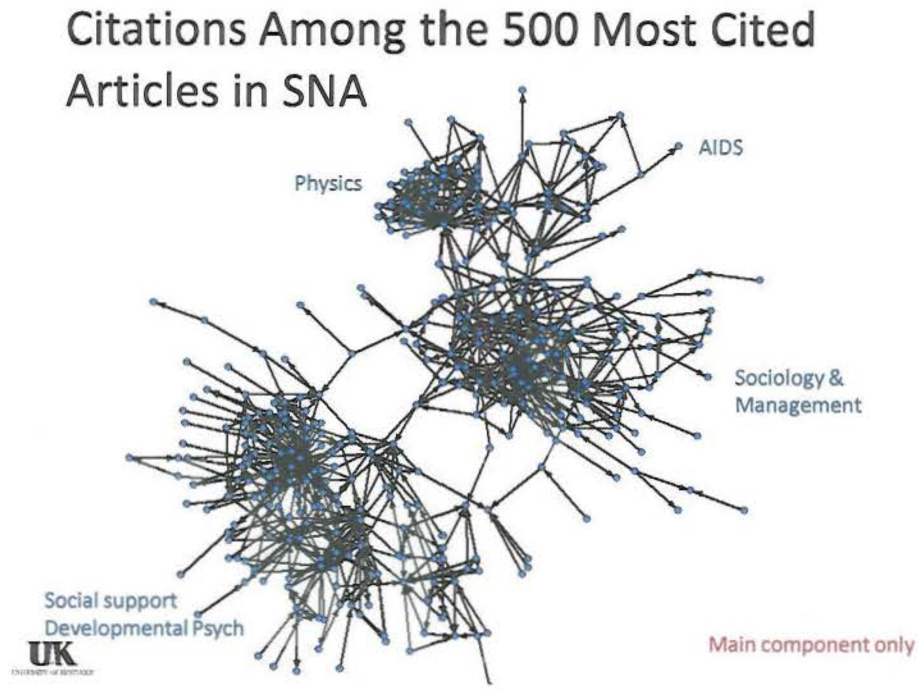

Figure 2: Citations among the 500 most cited articles in SNA

Despite this popularity (and, perhaps, in part because of it) there exists considerable confusion about network theorizing. Even though certain network theories are extremely well known – Granovetter's (1973) Strength of Weak Ties theory has been cited more than 14,000 times[1] – it is not unusual to read that network analysis contains no theory of its own (Salancik 1995). In this view, SNA is "just" a methodology, and what theory there is, "belongs to" other fields, such as social psychology. Moreover, as the term "social network" gains caché, it is increasingly applied to everything from a trade association to a listserv to a social media website such as Facebook.

Our objective in this report is to clarify the concept of social network, and to identify the characteristic elements of social network theorizing. We have a particular interest in explicating the mechanisms used in network theory so as to facilitate the

[1] Source: Google Scholar

generation of new theory applicable to DTRA's domain of interest. In characterizing network theory, it is important to emphasize that our objective is not to define what should and should not be network theory. We do elaborate a view of what constitutes the heart of network theorizing, but it is important to realize that the network analysis research program (in the sense of Lakatos 1980) is a social enterprise that includes all kinds of different researchers with different aims and backgrounds. There is a great deal of work that is part of the broader SNA research program that does not include the canonical elements we describe, or which includes additional elements that are not unique to the field.

3. Approach

In support of DTRA's objectives, the goal of our project was to examine existing social network theory to summarize and characterize it in such a way as to see commonalities and integrate where possible. To do this, we tried several different strategies for developing an integrated network theory. We outline the four main strategies here.

Expert Interviews

Our first approach involved interviewing social network analysis experts from a variety of fields. To accomplish this, we attended the Sunbelt Social Network Analysis Conference which attracts network experts in fields such as Anthropology, Communications, Computer Science, Epidemiology, Management, National Defense, Political Science, Sociology, and Statistics. We conducted taped interviews with 43 attendees, most of whom would be considered experts in the field (see Table 2 for a list of interviewed experts).

Last	First	Affiliation
Baker	Wayne	Management & Organization, University of Michigan
Barnett	George	Communication, UC-Davis
Bienenstock	Elisa	NSI; Management, Georgetown University
Bonacich	Phil	Sociology, UCLA
Brandes	Ulrik	Computer & Information Science, University of Konstanz
Brewer	Devon	Anthropology, University of Washington
Butts	Carter	Sociology, UC Irvine
Carley	Kathleen	School of Computer Science, Carnegie Mellon University
Casciaro	Tiziana	Management, Rotman School of Management, Canada
Daly	Alan (& 2 others)	Education Studies, UC San-Diego
Danowski	Jim	Communication, University of Illinois Chicago
Diani	Mario	Political Sociology, University of Trento, Italy

Doreian	Pat	Sociology, University of Pittsburgh
Ennis	Jim	Sociology, Tufts University
Everett	Martin	Manchester University, UK
Feld	Scott	Sociology, Purdue University
Galaskiewicz	Joe	Sociology, University of Arizona
Grant	Susan	Department of Defense
Greve	Arent (& Valdis Krebs, Bob Faris)	(Arent) Strategy and Management, The Norwegian School of Economics and Business Administration; (Valdis) Founder & management consultant, orgnet.com, USA; (Bob) Sociology, UC
Hennig	Marina	Institut fur Sozialwissenschaften, Humboldt University of Berlin
Hogan	Bernie	Oxford Internet Institute, University of Oxford
Johnson	Jeff	Sociology, East Carolina University
Kang	Soong	Enterprise and the Mgmt of Innovation, Stanford University
Kennedy	David	RAND Corporation
Koehly	Laura	NIH
Krackhardt	David	Organizations, Carnegie Mellon University
Lazega	Emmanuel	Sociology, University of Paris – Dauphine, France
Lazer	David	Kennedy School, Harvard University
Lloyd	Paulette	Sociology, UCLA
McCulloh	Ian	Network Science Center, West Point
Mohr	John	Sociology, Yale University
Monge	Peter	Communication, Management and Organization, University of Southern California
Morris	Martina	Sociology and Statistics, University of Washington
Reffett	Eric	Booz Allen Hamilton
Roberts	Nancy	Defense Analysis, Naval Postgraduate School
Robins	Garry	School of Behavioral Science, University of Melbourne
Skvoretz	John	Statistics, University of South Florida
Snijders	Tom	Statistics & Behavioral and Social Science, University of Oxford and Groningen
Talmud	Ilan	Sociology and Anthropology, University of Haifa
Tindall	David	Sociology, University of British Columbia
Valente	Tom	Preventive Medicine, University of Southern California
Wellman	Barry	Sociology, University of Toronto

Table 2: Social network analysis experts interviewed

The interviews addressed current perspectives about the field of network analysis and were aimed at identifying the key theoretical building blocks of network analysis. For example, experts were asked to identify distinguishing features of network theorizing as well as the necessary ingredients needed to construct a unified theory of networks. The experts were also asked about the feasibility and desirability of constructing a unified theory of network analysis. See Appendix B for our interview protocol.

We coded the 43 interviews for common themes using Atlas TI (See Figure 3 for an example). Results from the analysis of all interviews revealed a strong consensus that a unified theory of network analysis is not possible. Many experts commented that while a unified theory is desirable, social network analysis research involves too many wholly different dependent variables whose values are outcomes of totally different processes (See appendix for transcriptions of all interviews). Despite commenting on the challenges of such a project, the majority of experts felt that the process of investigating a unified theory was worth attempting (even if unlikely to succeed) and would provide opportunities to rethink the foundations of the field (because finding a basis for integration would require a deep understanding of the field). Some, however, felt that such an endeavor was undesirable and potentially risked the future of the field, referring to it as the "network science" trap, at term that social scientists use to refer to what they would regard as the naïve universalism of physicists who see universal laws in network phenomena. For more detail on the comments made by the interviewees, see Appendix 2.

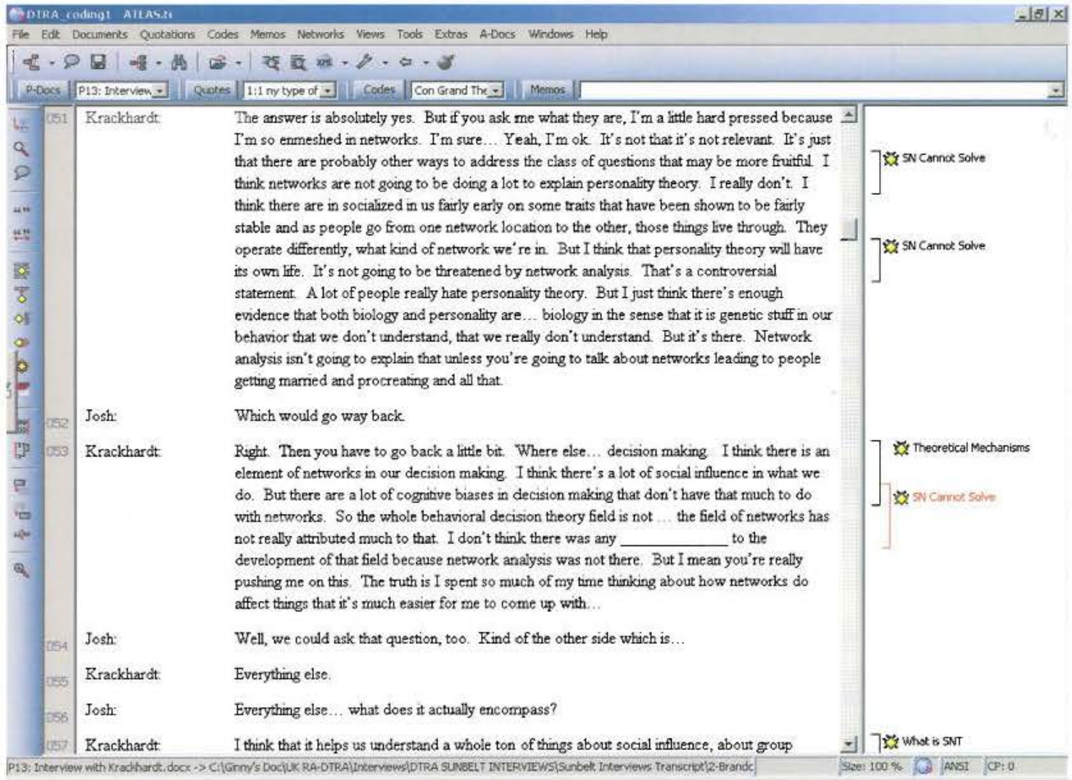

Figure 3: Coded DTRA interview in Atlas TI

Causal mapping

In addition to expert interviews, we conducted an extensive literature review of network analysis publications. On the assumption that a theory is a system of causally interconnected variables, one strategy for attempting to integrate network theory is to build a giant causal map – based on published articles -- relating network variables to each other and to antecedents and consequents. For example, a given article will express a hypothesis or proposition such as shown in Figure 4.

Proposition 3a: Restricted access reduces coordination costs of customized, complex exchanges. Ceteris paribus, restricted access enhances the likelihood of network governance emerging and thriving in rapidly changing markets for complex, customized tasks.

Figure 4: Example of research hypothesis

This can be visualized in the form shown in Figure 5.

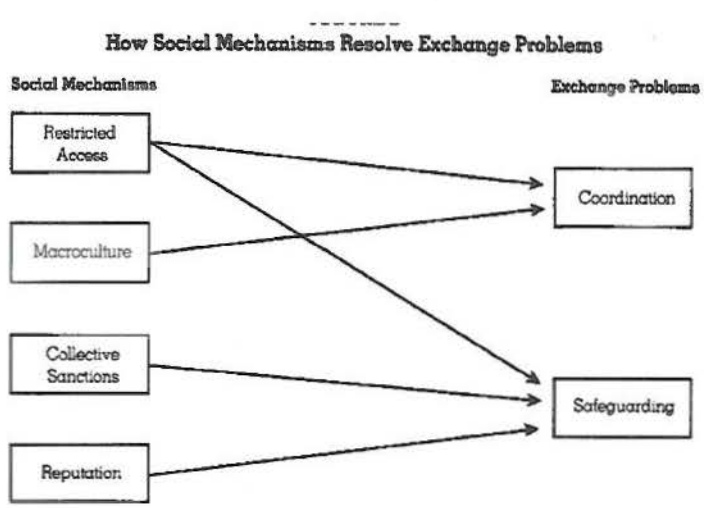

Figure 5: Example of visualized research hypothesis

To attempt to integrate the field as a whole, we collected the 500 most cited articles containing "social network" in the title, and examined the theory and hypotheses sections in order to extract key concepts and the causal relationships among them posited by the article (see Figure 6)

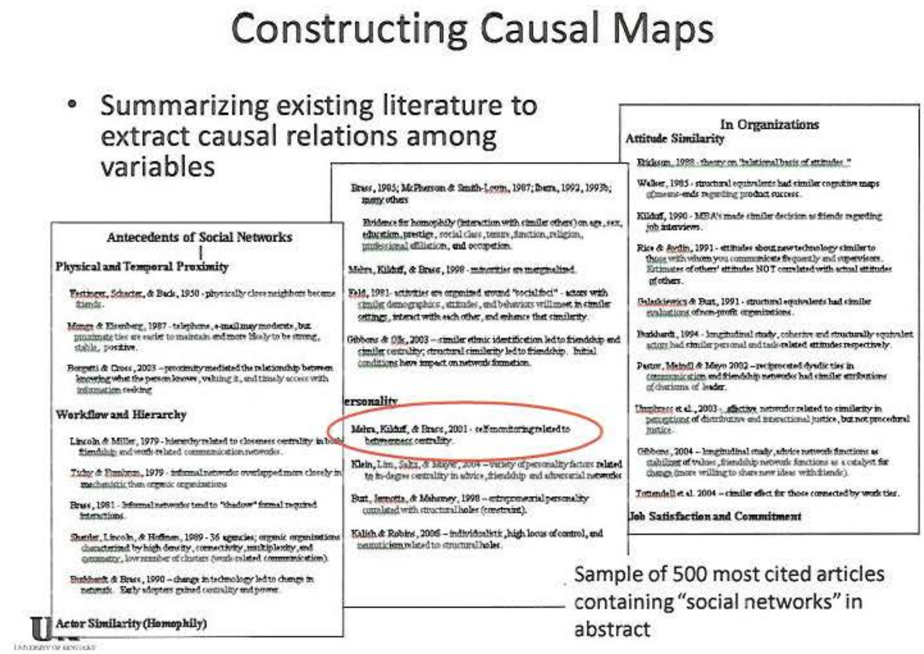

Figure 6

We then attempted to build integrated concept maps showing causal relationships among constructs across all articles. An example of such a map is given by Figure 7.

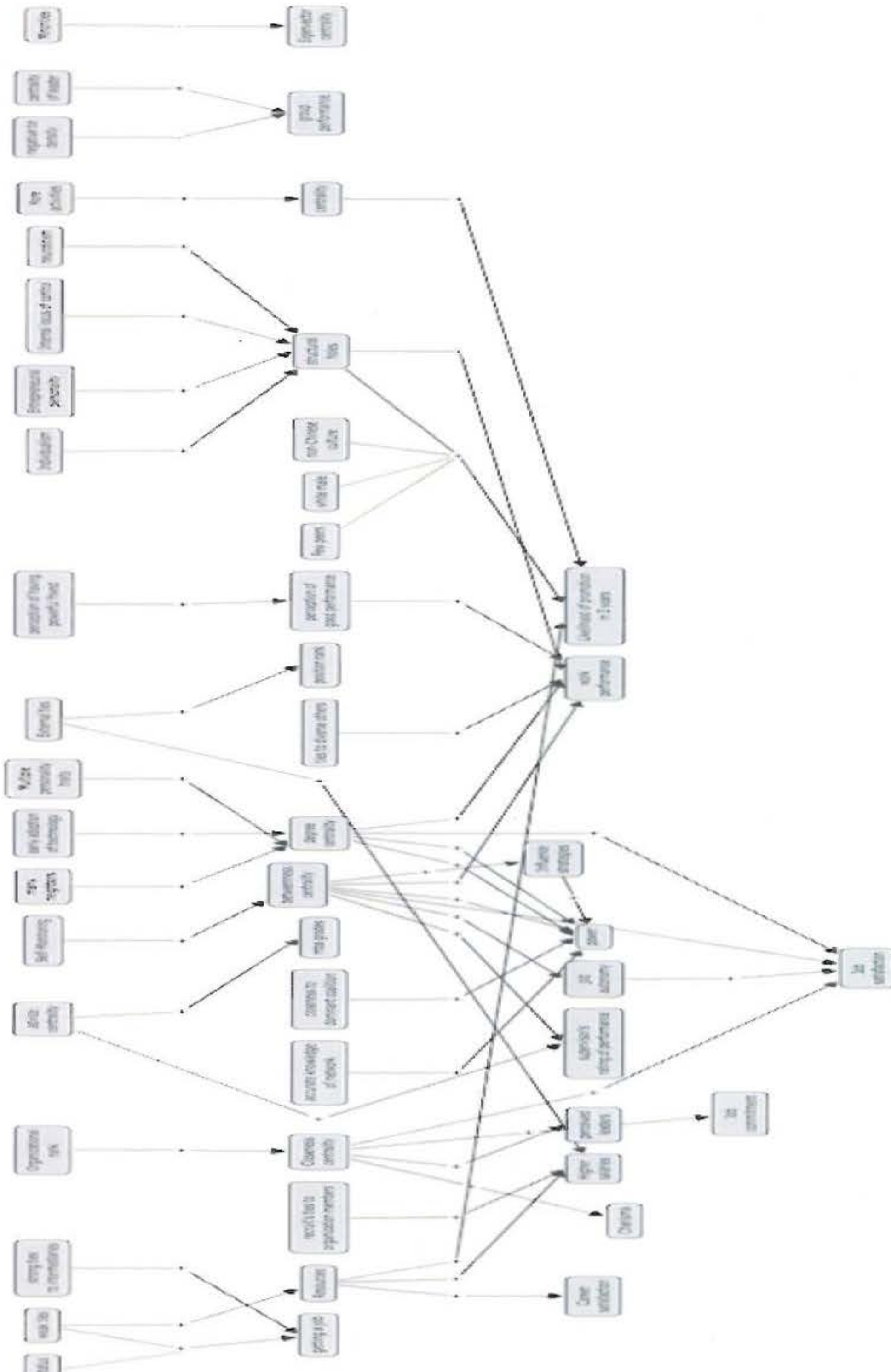

Figure 7: Concept map showing casual relationships

This approach runs into a number of serious problems. First, empirical results often contradict each other. For example, in one study variable X is shown to lead to Y. In another study, no connection between X and Y is found. For well-studied variables, it is possible to handle this with a heuristic such as majority rule (in combination with a statistical meta-analysis). In most cases, however, there is no clear majority. Sometimes the discrepancy between two studies can be put down to a contextual variable such as culture. For example, structural holes may lead to performance among US corporate managers, but not among French managers. Unfortunately, this also leads to enormous complication as every causal relationship is dependent on a host of contextual factors which would be expressed as moderator variables and, ultimately, interaction terms. The difficulty here is that multi-way interaction terms are extremely difficult to understand and don't provide a sense of simplifying explanation.

Another problem with this approach is that studies rarely use exactly the same variables. Even when two studies use the same words to describe the variables, what they actually measure is typically not the same. For example, two studies may study the relationship between centrality and status, but one measures degree centrality while the other measures betweenness centrality, which are such different concepts that calling them both centrality is misleading.

Finally, an enormous problem with this approach is that two studies can both posit that X leads to Y, but for different reasons. Since theory is fundamentally about the reasons why X leads to Y, in general this approach can be seen as missing the point. (However, sometimes a process that is postulated to convert X to Y can be proxied by a mediating variable Z, as when we argue that structural holes (X) leads to good job performance (Y) because individuals with many structural holes are in a position to accumulate more non-redundant information (Z). Hence, it was worth attempting this approach.)

Generic Mechanisms and Processes

In this approach we recognized that the essence of network theory is in the processes and mechanisms that take initial conditions, expressed as values of the independent or X variables, and yield outcomes, expressed as the value the dependent or Y variables. So we combed the literature for generic processes and outcomes. For example, a fundamental question in the social sciences is what accounts for similarities among actors (individuals, firms, nations, etc) in terms of behaviors, attitudes and beliefs. For example, why do some people use a new slang term. A generic answer in the social network literature is diffusion. A person who uses the new term has learned it from another, who learned it from another, and so on. Through social interaction, things spread from actor to actor.

Of course, each mechanism is itself a black box that needs explanation. For example, in the case of the diffusion of a bit of slang, not everyone who is exposed to the new term adopts it. The receiver of what is flowing has some choice in the matter and may actively reject innovations, or actively seek them out. Within the general category of diffusion there are many variant processes that can be elucidated. For example, we found four general variants in the network literature, distinguished by the extent to which the receiver of something flowing actively sought it out, or passively received, and whether the sender of what was flowing actively sought to have it adopted by others or passively let it happen. Table 3 shows the four resulting combinations. In the table, Ego represents the person adopting a new practice, and alter represents the people in their social environment – the people they have ties with and are receiving information from.

Alter (Social Environment)

Ego		Active (push)	Passive
	Active (pull)	**Accommodation Processes** E.g., apprenticeship; marriage; congressional politics	**Mimetic Processes** E.g., imitation, theft
	Passive	**Coercive Processes** E.g., threat	**Osmotic Processes** E.g., language acquisition, schemas

Table 3: Mechanisms/processes cross-classified by actor and environment agency

For example, the bottom left quadrant, labeled coercive processes, refers to the case where an actor does not necessarily want to adopt the new practice but has it pushed on them by another actor. An example is when a large retailer such as Walmart forces its suppliers to adopt a particular invoicing system that is finds convenient.

Each of these quadrants outlines a different sub-process or mechanism within the larger category of diffusion. And each is itself a black box that warrants further explication. For example, network researchers have investigated the top right quadrant, mimetic processes, in a number of contexts. Figure 8 outlines theory in the institutional theory realm of research which investigates the reasons why organizations copy structural and organizational elements from each other.

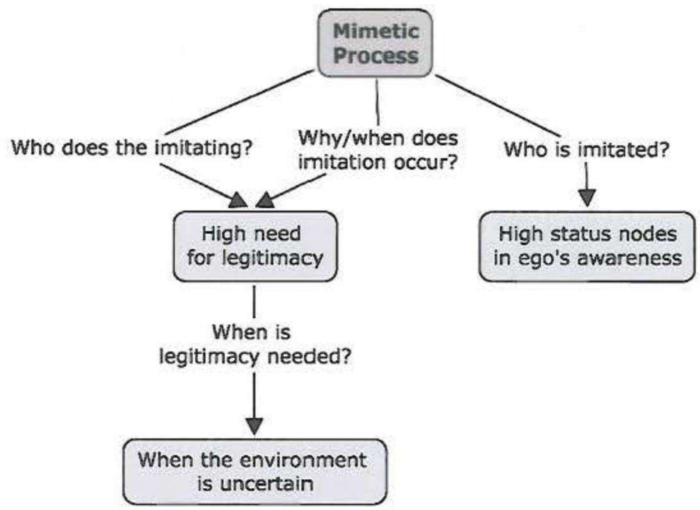

Figure 8

Taking this approach, we were able to isolate a large number of mechanisms, including sub-variants. These included:

- Capitalization. The process of a node actively seeking out and accumulating stocks of resources flowing to them through the network
- Sedimentation. Process of passively acquiring resources that flow to node
- Virtual Capitalization. Process of controlling others' resources as if they were a node's own (but without any actual transfer)
- Virtual Amalgamation and Exclusion. Process by tied nodes are able to act a single larger entity
- Staining. Process of acquiring features and characteristics of adjacent nodes through osmotic process
- Mimesis. Adoption of characteristics of adjacent nodes through a mimetic process
- Coercive isomorphism. Adoption of characteristics of adjacent nodes through coercion by the neighboring nodes

- Mutual Accommodation. Process of adopting neighboring nodes' characteristics through mutual pushing and pulling
- Convergence. Process of adapting to social environment such that nodes with similar environments develop similar characteristics

This seems quite a bit more useful than the causal mapping approach for several reasons, the main one being that this approach is more generative. Ultimately, DTRA needs to be able to apply social network theory to new situations. By focusing on mechanisms and generic processes, we elucidate the underlying principles that cause X to lead to Y, and these principles can easily be applied in new settings.

However, one problem does occur, and this is the problem of competing mechanisms. For example, an alternative to diffusion for explaining homogeneity is adaptation. Consider the case where persons A and B are both angry, and we seek to explain this similarity of states. The diffusion explanation is that one of them, say A, was angry, and this diffused to friend B. Or a third party C connected to both A and B was angry and this diffused simultaneously to both A and B. This is depicted in Figure 9.

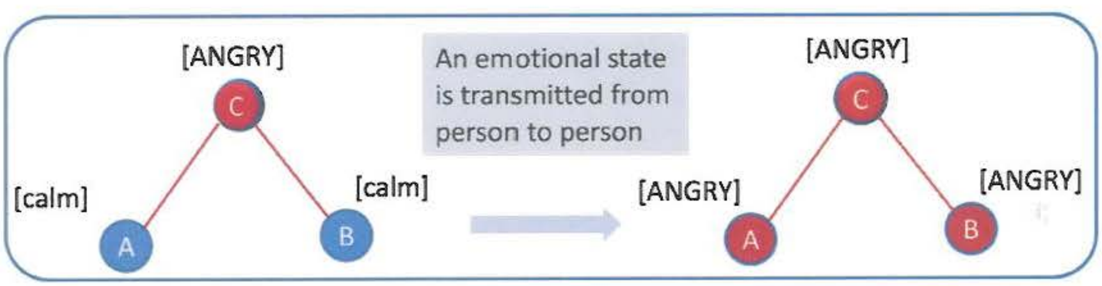

Figure 9

But another possibility is that C was not angry, but did something that annoyed A and B, causing them to respond with anger, as shown in Figure 10.

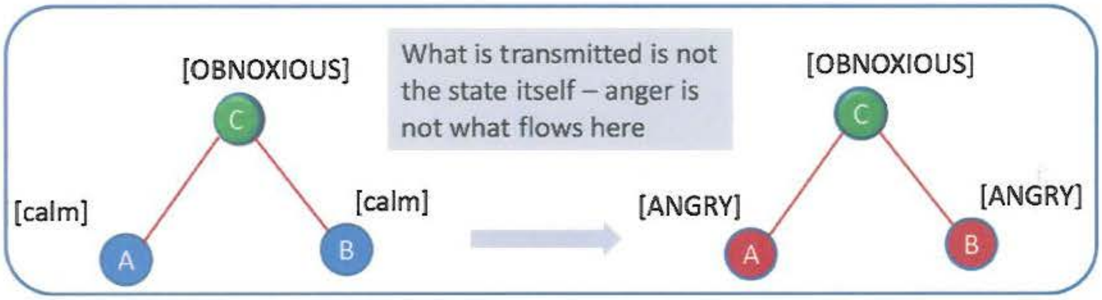

Figure 10

This is different from diffusion because anger did not flow. For another example, take the case of A and B who both hate the phone. Why do they share this attitude? The diffusion explanation is clear. But suppose A and B are in different social worlds with no connection to each other or common 3rd parties. Another – still network -- explanation is that both A and B are highly central in their respective advice networks such that people are always calling them for help. Over time, both respond to this common stimulus by learning to hate the phone. The underlying principle here is that A and B are not necessarily connected but have similar social environments, leading to similar responses on their part.

The problem this poses for the goals of this project is that we don't know which mechanism – diffusion or adaptation – to invoke when confronted when predicting an outcome in a given situation. And the two mechanisms do make different predictions. For example, given the same network structure (see Figure 11), the diffusion mechanism predicts that the nodes on the left and right sides of the network in Figure 11 will tend to be homogeneous within side.

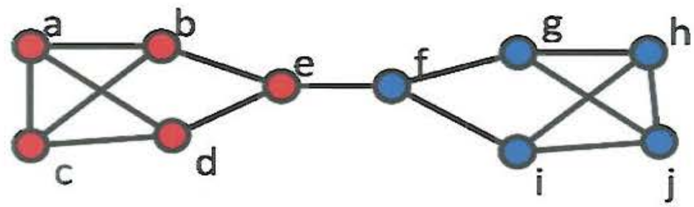

Figure 11

But given the same network structure, the adaptation mechanism predicts that the isomorphic nodes in the network (identified by color in Figure 12) will be homogeneous because they face similar environments.

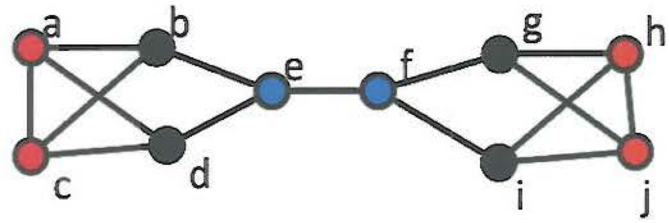

Figure 12

Model-Interface Decomposition

The final strategy we used, and the one that helped us move closest to our objective of an integrated network theory, draws inspiration from the principles of object-oriented programming. Essentially what we did was examine classic network theories, such as the strength of weak ties theory and the theory of structural holes, and tried to decompose these exemplars into a shared underlying abstract model plus a part that was unique to them. In a sense, we performed a mental factor analysis, trying to rewrite known theories as the union of two parts: an underlying shared factor or principal component and a unique factor.

In doing so, we found that the shared part corresponded to an abstract model, easily mathematizable and simulatable, and that the unique part corresponded to what might be called interface theory that mapped the constructs of the abstract model to constructs in the real world (or, at any rate, the world of social science concepts). For example, our analysis of one major network theory suggested a simple underlying model in which a system is modeled is a network of pipe-like ties through which things could flow. Given this mathematical model, it is possible to derive the consequences of structural features of the network on flow outcomes, such as how long it takes for something to reach a given node, or how often something will flow over a node.

Rewriting network theory in such a way that the abstract model is separate from the interface theory is a technique drawn from object oriented computer programming (OOP}. A key principle of OOP is that one should program to an interface rather than an implementation. What this means is that higher level code should not have to know the details of how lower level code works – the functions of the lower level code should be encapsulated so that higher level code deals only with the functions of the code, not the means by which they are accomplished. In network theory, the concept corresponding to OOP's object is the network, and what corresponds to OOP code is the set of processes or functions that we define on the network, such as flow of information. Thus, in the case of one network theory we will examine (the strength of weak ties theory), the underlying model is about generic nodes and ties that allow things to flow from one node to another. Certain minimal assumptions are made about the rules by which things flow, but we still keep the model at an abstract level that does not mention the meaning of ties (e.g. friendship and trust) nor discusses outcomes such as getting a job. It is kept generic. Then, to use the theory in a given setting, we use an interface theory to tie these model constructs to real world implementations, such as getting a job. The advantages of this approach are discussed in a later section.

4. Fundamentals of Network Theory

With this section, we begin reporting the results of applying the strategies outlined in Chapter 3.

SNA theorizing encompasses two (analytically) distinct domains, which we refer to as "network theory" proper and "theory of networks". Network theory refers to the mechanisms and processes that interact with network structures to yield certain outcomes for individuals and groups. In the terminology of Brass (2002), network theory is about the consequences of network variables, such as having many ties or being centrally located. In contrast, theory of networks refers to the processes that determine why networks have the structures they do – the antecedents of network properties, in Brass's terms. This includes models of who forms what kind of tie with whom, who becomes central, and what characteristics (e.g., centralization or small-worldness) the network as a whole will have. In this report, we focus on network theory proper, although we do find it useful in parts to make a few comments about theory of networks as well. In addition, we devote a section of this report to assessing whether considering network theory without simultaneously treating theory of networks does harm to understanding of either.

Networks Versus Groups

A network consists of a set of actors or nodes along with a set of ties of specified type (such as friendship, communicate with, send money to) that link them. The ties interconnect through shared endpoints to form paths that indirectly link nodes that are not directly tied. The pattern of ties in a network yields a particular structure, and nodes occupy positions within this structure. Much of the theoretical wealth of network analysis consists of characterizing network structures (e.g., small worldness) and node positions (e.g., centrality) and relating these to group and node outcomes.

It is important to realize that it is the researcher – by choosing a set of nodes and a type of tie – that defines a network. To appreciate the point, consider the boundary specification problem (Laumann, Marsden, and Prensky 1983), which refers to the question of how to select which nodes to study. The naïve concern is that we may select nodes "incorrectly", accidentally excluding nodes that should have been there and possibly including nodes that should not have been. In reality, however, the choice of nodes should not generally be regarded as an empirical question. Rather, it should be dictated by the research question and one's explanatory theory. For example, we may be interested in how centrality in an organizational communication network is related to work performance. Therefore, we study all communication ties among all members of the organization. In making this choice, no claim is made that only ties with other members of the organization exist or matter, but rather that position in the network defined by this kind of tie among this set of actors has a measureable effect on performance. A different researcher might be interested in how a person's communications outside the organization interact with the intra-organizational communication network to affect performance. Yet another researcher, perhaps a psychologist, might ignore the influence of others altogether (whether inside or outside the organization) and focus on how personality or life experiences affect a person's performance.

In our view, part of the angst involved in the boundary specification problems is due to confusing networks with groups. A fundamental part of the concept of group is the existence of boundaries. Even while we recognize that boundaries may be fuzzy or uncertain (e.g., there are part-time members, wannabees, conflicting views of what the group is, etc), the distinction between insiders and outsiders is an important part of the group concept. Therefore, when studying groups, we are justifiably concerned with establishing the boundaries of the group. For example, if we are studying gangs in Los Angeles, we would not want to approach the boundary specification problem in a wholly etic[2] way, such as defining gang members as all young males living in a given area.

In contrast to groups, networks do not have "natural" boundaries (although, of course, we are free to study natural groups, in which case the group boundaries determine our nodes).[3] Networks also don't have to be connected. A disconnected network is one in which some nodes cannot reach certain others by any path, meaning that the network is divided into fragments known as components (see Figure 13). For those confusing networks with subgroups, this may seem an odd conceptualization of networks. The advantage, however, is that it facilitates the study of network evolution. For example, suppose we study the freshman class at a university, focusing on friendships. Initially, it may be that none of the freshmen are friends with any other, defining a maximally disconnected network with as many components as nodes. Over time, friendships begin

[2] Etic versus emic is a distinction made in cognitive anthropology between organizing the world using researcher-driven criteria (etic) and organizing things the way natives do (emic). The terms come from the linguistic distinction between phonetic (how things sound) and phonemic (how things mean).

[3] It should be acknowledged, however, that there is a literature that labels organizational forms intermediate between hierarchies and markets as "networks". In this literature, a network refers to a group of organizations working closely together, almost as if they were one super-ordinate organization.

to develop and the number of components may reduce rapidly. Eventually, it is possible that all of the actors are connected in a single component in which every node can be reached from every other by at least one path (even if very long). Thus, by allowing the network to be disconnected, we can trace the evolution of connectivity within it. Thus, in this perspective, we do not ask "under what circumstances will networks emerge" (DTRA, 2006), as if they were groups. Rather, we ask how specific properties of the network, such as level of fragmentation or characteristic path length, change over time.

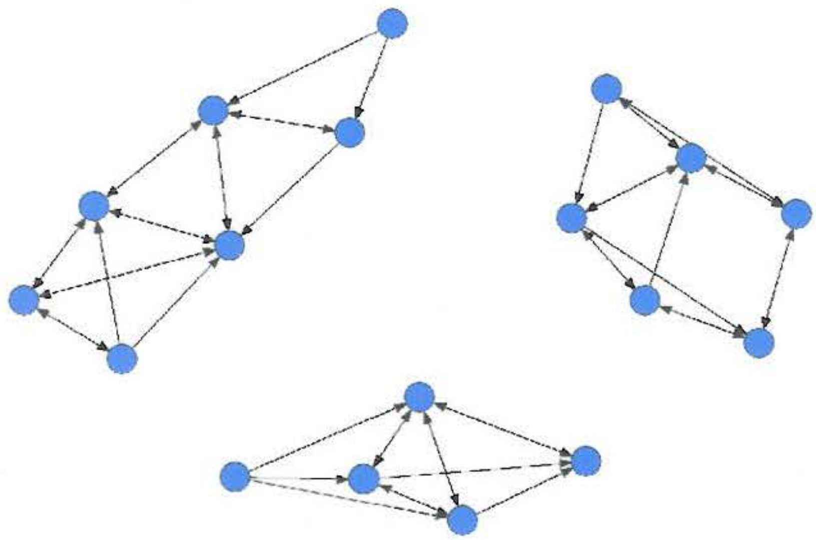

Figure 13: Network with three components

Types of Ties

A closely related issue is what "counts" as a tie. A common beginner's question is 'which network questions should I ask in order to get at the network'. Implicit in the question is the idea – labeled the *realist* position by Laumann et al., (1983) – that there is a "true" network of relationships out there and our job as researchers is to discover it. Given that, it is reasonable to ask which social network questions have proven effective at eliciting this network. However, a more sophisticated view of social networks – labeled the *nominalist* position by Laumann et al., (1983) -- holds that every network question (such as "who are you friends with?" or "who do seek advice from?") generates its own network, and which to use is determined by the research question. Thus, a given research question may lead us to examine the advice and friendship ties within an organization, while another research question may lead us to examine 'who likes whom' ties. No matter what kind of tie we are interested in, measuring that kind of tie among all pairs of nodes in the sample defines a network, and each network will have its own structure and its own implications for the nodes involved. For example, being central in a gossip network might be entertaining and beneficial, while being central in a who-dislikes-whom network might be painful and deleterious.

In practice, the kinds of ties that network theorists tend to focus on can be categorized into two basic types: states and events (see Table 4). States have continuity over time. This is not to say they are permanent but rather that they have an open-ended persistence. Examples of state-type ties include kinship ties (e.g., parent of), other role-based relations (e.g., friend of; boss of), cognitive/perceptual relations (e.g., recognizes; knows the skills of) affective relations (e.g., likes; hates), and similarities. State-type ties can be dimensionalized in terms of strength, intensity, and duration.

State-Type Ties	Event-Type Ties
• Role-based ties (e.g., kinship, boss of; friend of) • Cognitive (e.g., knows) • Affective (e.g., likes, dislikes) • Similarities	Interactions (e.g., giving advice to; sending email; signing treaty with; making a sale)

Table 4: Types of social ties

Role-based ties include kinships and role relations such as *boss of*, *teacher of*, and *friend of*. We use the term *role-based* because these relations are usually institutionalized into rights and obligations, and are linguistically identified as, for example, *friend*, *boss*, or *uncle*. Many are also symmetric or skew-symmetric, such that if A is a friend of B, then B is a friend of A, and if A is the teacher of B, then B is the student of A. Another characteristic of role-based relations is that they are in a weak sense public and objective—a researcher can ask a third party whether two people are friends or have a teacher/student relationship and not receive an automatic "how should I know?" reaction.

Cognitive/perceptual relations and *affective relations* consists of perceptions and attitudes about specific others, such as *knowing*, *liking*, or *disliking*. These evaluations are widely considered private, idiosyncratic, and invisible. They can easily be nonsymmetric: A likes B, but the reverse may or may not be true.

Similarities can refer to physical proximity, co-membership in social categories, and sharing of behaviors, attitudes, and beliefs. Generally, we do not see these items as social ties, but we do often see them as increasing the probabilities of certain relations and dyadic events. For example, in an organizational setting, Allen (1977) found that communication tends to increase as a function of spatial proximity.

In contrast, an event-type tie has a discrete and transitory nature and can be counted over periods of time. Examples of event-type ties include email exchanges, money transfers, phone conversations, and transactions such as sales or treaties signed. Cumulated over time, event-type ties can be dimensionalized in terms of frequency of occurrence (e.g., number of emails exchanged, amount of money exchanged). It is these kinds of ties that researchers have in mind when they define networks as "recurring patterns of ties" (e.g., Dubini and Aldrich 1991; Ebers 1997; Jaffee, McEvily, Tortoriello 2005).

Both state-type ties and event-type ties can be seen as roads or pipes that enable (and constrain) some kind of flow between nodes.[4] Flows are what actually pass between nodes as they interact, such as ideas or goods. Hence two friends (state-type social relation) may talk (event-type interaction) and, in so doing, exchange some news (flow). As we discuss in the next section, one large swath of network theory is about how position in a backcloth network determines the timing or quantity of flows to the actor occupying that position.

We might also note that, in empirical studies, researchers often make use of relational states and events that are not, properly speaking, social ties. For example, a frequent proxy for social ties is group co-membership, such as being on the same board of directors or belonging to the same club. Similarly, co-participation in events, such as parties, is used as a proxy for unobserved social relationships. Other dyadic variables of this type include geographic proximity (Allen 1977) and similarity of traits such as behavior, beliefs and attitudes (McPherson and Smith-Lovin 1987; McPherson, Smith-Lovin and Cook 2001). From a theoretical point of view, co-memberships, co-participations, geographic proximities and trait similarities can all be seen either as dyadic factors contributing to the formation of ties (e.g., meeting the other members of your club), or as the visible outcomes of social ties (as when close friends join the same groups or spouses come to hold similar views).

[4] This is Atkin's (1972) "backcloth/traffic" distinction.

Scholars have also differentiated dyadic phenomenon as *backcloth* and *traffic* (Atkin 1974, 1977). The backcloth consists of an underlying infrastructure that enables and constrains the traffic, and the traffic consists of what flows through the network, such as information. For example, in weak tie theory, social ties such as acquaintanceships serve as potential conduits for information. A more elaborate set of distinctions is illustrated in Figure 14X, which divides dyadic phenomena into four basic categories: similarities, social relations, interactions, and flows.[5]

Figure 14: Types of dyadic phenomena.

In Atkin's view, the four dyadic phenomena all serve as the backcloth for the phenomena to their right. Hence, physical proximity can facilitate the development of certain relationships, and certain relationships permit certain interactions; these in turn provide the vehicle for transmissions or flows. However, it is also clear that phenomena on the right can transform the phenomena on the left, so that people with certain relationships (e.g., spouses) tend to move closer together, and certain interactions (e.g., sex) can change or institutionalize relationships.

Much of network theory[6] focuses on either social relations or interactions, using these ties to define the network backcloth, which then determines flows. Interactions are transitory, so theory built on them typically conceptualizes them as cumulative over time, describing them as *recurrent*, *patterned*, or *relatively stable*. In effect, this relation

[5] It is useful to note that the two categories on the left make up relational phenomena that, while they exist, exist continuously, like states. The phenomena on the right tend to be transitory and discrete, as in events.
[6] In particular, the body of theory based on the flow model described in Chapter 6.

converts into an underlying social relation that is ongoing across interaction episodes. Flows matter in most network theories but are generally assumed immeasurable in practice.

We emphasize three points based on this discussion. First, much of network theory exists as a solution to the fact that we do not measure flows directly.[7] Hence we build theory that links the observable network of social relations to these latent flows. If the flows were directly measurable, we would not need to infer that nodes with more structural holes (or weak ties) would receive more information: we would simply measure the information they got.

Second, much of network theory depends on the relative permanence of ties. For example, consider a node that profits from being the broker between otherwise unconnected nodes. This works only if the spanned nodes cannot simply create a tie with another at will. If a direct tie can always be formed, the importance of paths through a network vanishes, as does the importance of structure in general.

Third, when researching the exploitation of network position by nodes, it is problematic to measure relational *events* such as interactions and flows rather than relational states, because power use can change the event network. For example, if a node tries to extract rents for being between two others, the others may choose a different path (Ryall and Sorenson, 2007; Reagans and Zuckerman, 2008). So the event network we see is not the potential structure defined by underlying relations, but an actualized instance that could change at any time and therefore does not tell us what other paths might have been possible.

[7] This is in part for reasons of convenience. For example, it is time-consuming and therefore rare to track a specific bit of information as it moves through a gossip network. However, some settings lend themselves to observing flows, as in the movement of goods in the world economic trade network.

Levels of Analysis

Levels of analysis are so basic as to often escape notice. However, in the network case there are some subtleties that make the dimension worth attending to. We start by observing that network data are fundamentally dyadic, meaning that we observe a value for each *pair* of nodes (e.g., whether actor A and actor B are friends or not; the number of e-mail messages exchanged by actor A and actor B), rather than for each node (e.g., age or gender of each actor). Hence, we can clearly formulate hypotheses at the dyadic level. Dyadic hypotheses essentially predict the ties of one social relation with the ties of another relation measured on the same actors. For example, Gulati and Gargiulo (1999:1446) hypothesize that previous ties among two organizations increase the probability of an alliance between them in the future. But since the data can be aggregated to higher levels, hypotheses can be tested not only at the dyadic level but at the actor and whole network levels as well (not to mention mixed-level hypotheses, as when we use gender to explain who talks to whom).

In traditional research, we typically define levels of analysis in terms of the scope and complexity of the entities being studied (hence organizations represent higher levels than persons), and this dimension tends to be an important distinction among studies and their authors (leading to frequent efforts to "bridge the micro-macro gap"). However, in network research the situation is subtly and deceptively different, because the obvious levels of analysis (dyadic, actor and network) do not necessarily correspond in a simple way to the type of entities being studied. For example, suppose we examine how an actor's centrality in the communication network of an organization relates to her ability to innovate and solve problems (e.g., Perry-Smith & Shalley, 2003). This is an actor-level analysis, one step up (i.e., more aggregate, fewer values) from the dyadic level. Now suppose we look at the communication networks of the top management team in 50 separate firms and correlate the density of each network with some aspect of firm performance (e.g., Athanassiou and Nigh, 1999). This, as we would expect, is a network- or group-level analysis, a step up from the actor level. But now suppose we do a network analysis of alliances among biotech firms, hypothesizing that firms with more alliance partners will be more successful (e.g., Powell et al., 1996). Surprisingly, we are now back at the actor level of analysis, probably invoking the same arguments that were used for the first actor-level hypothesis. This is not unusual in network research, where micro and macro can be very similar theoretically and methodologically (see Katz & Lazer, 2003, for a similar point of view). This does not mean that we expect every theory that applies to networks of persons to apply as well to networks of organizations, since the agents have different capabilities and the relations have different meanings. It is just that structural explanations are much more likely to scale than are individualist or essentialist explanations, a fundamental tenet of the physics literature on networks (Barabasi, 2002).

Direction of Causality

A fundamental dimension distinguishing among network studies is whether the studies are about the causes of network structures or the consequences. The bulk of network research has been concerned with the consequences of networks. One reason for this has to do with networks being a relatively young field whose first order of business was to achieve legitimacy. A rational strategy for gaining legitimacy is to show that network variables have consequences for important outcome variables that traditional fields already care about. Until networks had legitimacy, there was little point in trying to publish papers on how networks come to be or change over time.

Another reason for favoring consequences has been the structuralist heritage of the field. Since sociologists began to dominate network research in the 1970s, the proposition that an actor's position in a network has consequences for the actor has occupied a central place in network thinking. This is the structuralist paradigm championed by Blau (1977) and especially Mayhew (1980) and expressed in the network context by Wellman (1988). In general, networks are seen as defining the actor's environment or context for action and providing opportunities and constraints on behavior. Hence, studies that examine the consequences of networks are typically consistent with the structuralist agenda. In contrast, studies that examine the causes of network variables often clash with structuralism because they explain the network in terms of actor personalities and latent propensities (e.g., Mehra et al., 2001), which is anathema to the strong structuralist position (Mayhew, 1980).

To be fair, though, there is much more work on network antecedents than people give the field credit for, and the volume is increasing rapidly. The work is not very visible in part because there isn't a single area of research called 'network change'. Rather, work on change is embedded in the various substantive areas (e.g., Gulati & Gargiulo, 1999; Madhavan, Koka, & Prescott, 1998; Shah, 2000). For example, the majority of recent work on inter-organizational networks is about explaining how and why organizations form ties and select partners (whether interlocking directorates or alliances or supply chains). Similarly, the large literature on the effects of proximity and homophily

(McPherson, Smith-Lovin & Cook, 2001) is about network causes, as is the growing area of agent-based models of networks (Macy & Willer, 2002). In addition, almost all of the hundreds of articles on networks contributed by physicists in the last few years are focused on the evolution of networks (for a review, see Newman, 2002).

Explanatory Goals

Consider the difference between a social capital study such as Burt's (1992) attempt to explain promotion rates in terms of aspects of an actor's ego-network and a diffusion study such as Davis's (1991) study of the diffusion of corporate practices like poison pills through board interlocks. We point to two key differences.

First, the perspective in the social capital study is more evaluative, concentrating on the benefits of social position. Indeed, the evaluative aspect is prominent in virtually all social capital studies, including those focusing on the so-called "dark side". In contrast, the diffusion study is more interested in the process by which practices, for good or ill, spread through a system.

Second, the social capital study emphasizes the possibilities for action that social ties provide the individual, whereas the diffusion study is implicitly about how the network changes the actor (in the sense of adopting a practice or developing an attitude). Like social attitude formation (Erickson, 1988) and social influence studies (Friedkin & Johnsen, 1999), network diffusion studies are exemplars of a structuralist tradition that emphasizes constraints (DiMaggio and Powell, 1983:149), while the social capital literature concentrates on opportunities (Gargiulo & Benassi, 2000). The actor in social capital work is generally a very active agent who exploits the network position she finds herself in (or creates for herself). While Burt (1992) stops short of saying so, many of his readers (e.g., Steier & Greenwood, 2000) seem to add a rational actor assumption to social capital theory to the effect that actors deliberately choose their ties (i.e., manipulate the network structure) specifically in order to maximize gain. This instrumental, individual-oriented aspect of social capital work contrasts with the environmental determinism that is found in much diffusion (e.g., Valente, 1995) and social influence (Friedkin & Johnsen, 1999) research.

In general, the difference between the social capital and diffusion studies mirrors the traditional difference between the fields of strategy and organization theory (particularly institutional theory), and the classical tension between agency and structure. More concretely, the distinction can also be framed in terms of the goals of the research. Social capital studies seek to explain variation in success (i.e., performance or reward) as a function of social ties, whereas diffusion and social influence studies seek to explain homogeneity in actor attitudes, beliefs and practices, also as a function of social ties. While variation and homogeneity are two sides of the same coin, the difference in perspective is telling.

5. Analysis of Canonical Network Theories

To illustrate the nature and distinctive flavor of network theorizing, we start by describing in detail three well-known network theories, and then analyze them for their key characteristics. We begin with Granovetter's (1973) Strength of Weak Ties theory (SWT), and then move to Burt's (1992) Structural Holes theory and Milgram's (1967) Small Worlds research.

Strength of Weak Ties (SWT)

The SWT theory is organized as a set of explicit premises and conclusions (see Figure 15). The first premise of the theory is that the stronger the tie between two people, the more likely their social worlds will overlap – that they will have ties with the same third parties. As a result, if A and B have a strong tie, and B and C have strong tie, the claim is that A and C have an increased chance of having at least a weak tie (e.g., A and C are acquaintances). This is a kind of transitivity – one that some authors have called g-transitivity (Freeman 1979).

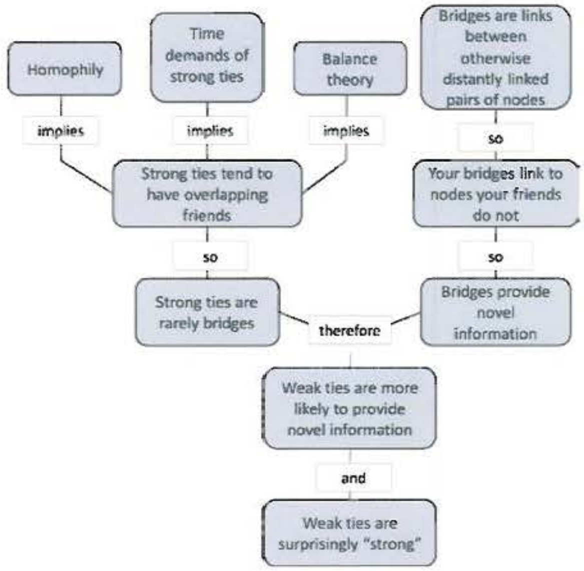

Figure 15: Granovetter's (1973) Strength of Weak Ties theory.

The reason for this transitivity, Granovetter argues, is that the underlying causes of tie formation have this kind of transitivity built into them. For example, people tend to be *homophilous*, meaning that they tend to have stronger ties with people who are similar to themselves (Lazarsfeld and Merton 1954; McPherson et al., 2001). Homophily is weakly transitive because if A is similar to B, and B is similar to C, then A and C are likely to be somewhat (i.e., weakly) similar as well (see Figure 16). To the extent that similarity causes ties, this will induce weak transitivity in the tie structure as well. Another argument is based on balance or cognitive dissonance theory (Heider, 1958; Cartwright and Harary, 1956; Newcomb, 1961; J. Davis, 1967). If A likes B, and B likes C, A would like to like C as well to avoid dissonance.

Figure 16: One premise of Granovetter's (1973) SWT theory.

The second premise of SWT is that bridging ties are a potential source of novel ideas. A bridging tie is a tie that links a person to someone who is not connected to their other friends.[8] The idea is that, through a bridging tie, a person can hear things that are not already circulating among his close friends. In Figure 17, A's tie with G is a bridging tie. Since A is the only person in her social group with a tie outside the group, A has the benefit of hearing things from G that the rest of A's group has not yet heard.

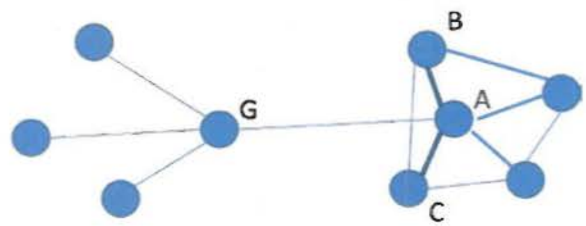

Figure 17: Bridging tie from A to G. Removing the tie disconnects the network.

Putting the two premises together, Granovetter reasoned that strong ties are unlikely to be the sources of novel information. The reason is as follows. First, bridging ties are unlikely to be strong. According to the first premise, if A and G have a strong tie, then G should have at least a weak tie to A's other strong friends, which would imply that the A-G tie was not a bridge, since there would be multiple short paths from A to G via

[8] More technically, a bridge is a tie between A and B, which, if removed, would leave a very long path (if any at all) connecting A to B. A bridge, then, is a shortcut in the network.

their common acquaintances. Therefore, it is only weak ties that are likely to be bridges. Second, since bridges are the sources of novel information, and only weak ties are bridges, it is the weak ties that are the best potential sources of novel information.[9] Granovetter uses this theory to explain why people often get or at least hear about jobs through acquaintances rather than close friends. In this sense, the theory is one of individual social capital, where people with more weak ties (i.e., more social capital) are more successful. Granovetter also applies the theory at the group level, arguing that communities with many strong ties have pockets of strong local cohesion but weak global cohesion, while communities with many weak ties have weak local cohesion but strong global cohesion. Using the case study of Boston in which the city assimilated one adjacent community but failed to assimilate another he suggests that a community's diffuse, weak-tie structure constitutes group-level social capital that enables the group to work together to achieve goals, such as mobilizing resources and organizing community action to respond to an outside threat.

Structural Holes

Another well-known network theory is Burt's (1992) structural holes theory of social capital (SH). The theory of SH is concerned with ego-networks – the cloud of nodes surrounding a given node, along with all the ties among them. Burt argues that if we compare nodes A and B in Figure 18, the shape of A's ego-network is likely to afford A more novel information than B's ego-network does for B, and as a result A may perform better in a given setting, such as an employee in a firm. Both have the same

[9] Note that there is no claim that all weak ties are sources of novel information – just the ones that happen to be bridges. Granovetter's point is simply that it is weak ties rather than strong ties that are more likely to be bridges.

number of ties, and we can stipulate that their ties are of the same strength. But because B's contacts are connected with each other, the information B gets from, say, X may well be the same information B gets from Y. In contrast, A's ties connect to three different pools of information (represented by circles in Figure 18). Burt argues that, as a result, A is likely to receive more non-redundant information at any given time than B, which in turn can provide A with the capability of performing better or being perceived as the source of new ideas.

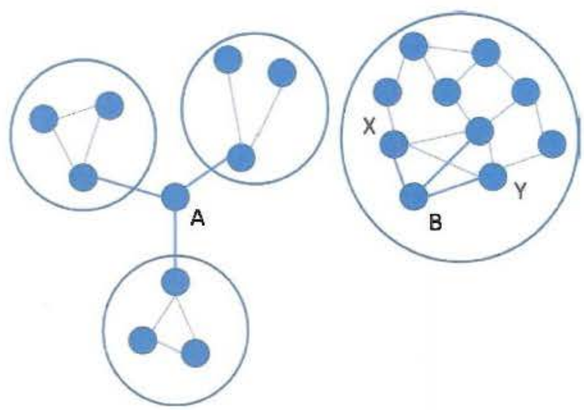

Figure 18: Node A's ego-network has more structural holes than B's.

Kilduff (2010) argues that Burt's portrayal of the social world differs significantly from that of Granovetter along a variety of dimensions. For example, Kilduff sees Granovetter as embracing a serendipitous world in which people form ties that only incidentally prove useful, while Burt embraces a more strategic and instrumental view. However, at the level of the specific theories of SWT and SH, it should be obvious that Burt's theory is closely related to Granovetter's. In Burt's language, A has more structural holes than B, which means A has more non-redundant ties. In Granovetter's language, A has more bridges than B. But whether we call them non-redundant ties or bridges, the concept is the same, and so are the consequences: more novel information. Where Granovetter and Burt differ is that Granovetter further argues that a tie's strength determines whether it will serve as a bridge. Burt does not disagree and even provides empirical evidence that bridging ties are weaker in that they are more subject to decay (Burt 1992, 2002). However, Burt sees tie strength as a mere "correlate" of the underlying principle, which is non-redundancy (1992, p. 27). Thus, the difference is between preferring the distal cause (strength of ties), as Granovetter does, and the proximal cause (bridging ties), as Burt does. The first yields an appealingly ironic and counterintuitive story line, while the second "captures the causal agent directly and thus provides a stronger foundation for theory" (Burt 1992, p. 28). In addition, Granovetter uses getting jobs as an outcome of having non-redundant information, while Burt uses getting promoted. In our view, these are small differences in ornamentation. Both theories are based on the same underlying model of how networks work.

Small Worlds

Another well-known area of network theorizing is small-world theory. In the 1950s and 1960s, a stream of mathematical research sought to explain coincidences of mutual acquaintanceship (de Sola Pool and Kochen, 1978[10]; Rapoport and Horvath, 1961). The basic thrust of the research was to show that societies were probably much more close-knit than popularly believed. A field experiment by Milgram (1967; Travers and Milgram, 1969) supported this theory, finding that paths linking random Americans

[10] Original paper written in 1958 and well circulated for 20 years before publication in 1978 in the inaugural issue of *Social Networks.*

were incredibly short. Restarting this stream of research 20 years later, Watts and Strogatz (1998) asked how human networks could have such short average distances, given that human networks were so clustered, a property that was known to lengthen network distances (Rapoport and Horvath, 1961). The answer, Watts and Strogatz showed, was simple: adding even a small number of random ties to a heavily clustered network could radically reduce distances among nodes. The reason was that many of these random ties would be between clusters, which is to say, they were bridges.

Common Elements

Examining SWT and SH from a meta-theoretical point of view, we can see two features of network theory that are highly characteristic. First, the twin notions of structure and position play a fundamental role. For example, in SWT, the reason why weak ties are useful is not because they are inherently so, but because it is the weak ties that tend to bridge between network clusters. It is their structural role that makes them advantageous. Similarly, in SH, it is the shape of the ego-network around a person that confers advantages to the person. Note that the theory ignores ego's own attributes (such as how creative they are) and also the attributes of ego's contacts (e.g., how smart they are, how gullible, how powerful) and only looks to see whether the alters are numerous and unconnected. This is not to say that ego and alter attributes are not important (they may well be much more important); it is just that the agenda of the theory – and the charter of network theory in general – is to explicate the connection between structure and outcome, and one aspect of this agenda is the study of the pure effects of structure. To be clear, the general agenda of examining the consequences of network structure includes the examination of how structure and attributes interact to yield outcomes. But a piece of that investigation is the exploration of how structural differences alone have effects.[11]

Second, there is an implicit theory of network function; in the case of SWT and SH (but not all network theories), that network function is the flow or distribution of information. In effect, SWT and SH rely on an underlying model of a social system as a network of paths which act as conduits for information to flow. We refer to this as the "flow model".

6. The Network Flow Model

The flow model essentially views a network as a system of pipes (or roads) through which things can flow. What flows can be material things, such as guns, money and personnel, or immaterial things like ideas, beliefs, information, attitudes and so on. We limit the network flow model to "true" flows in the sense that what arrives at the other end is essentially the same as when it started. Whatever flows through the network may be damaged or changed en route, but it remains basically the same thing. If it starts as gossip, it arrives as gossip, even if the details have changed. The distinction we are making is with a more general sense of flow such as a chain of causality, where, for example, someone misses an appointment and sets off a chain of events that culminate in a civil war. We regard this more general sense of flow as constituting a different model.

The flow model carries with it some basic assumptions, such as the longer a path, the longer it takes something to traverse it. From this general model we can readily derive

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[11] We are grateful for an anonymous reviewer for pointing this out.

a number of theoretical propositions that form the core of theories like SWT and SH. For instance, nodes that are far from all others will, on average, receive flows later than nodes that are more centrally positioned. Similarly, nodes that are embedded in locally dense parts of a network will often receive the same bits of flow from their various contacts, because the contacts are tied to each other as well.

The abstract flow model also carries with it a set of natural outcome variables. For instance, at the node level, we may be interested in the expected time until (first) arrival of whatever is flowing through the network. Certain (central) nodes are positioned in such a way that, on average, they receive the flow sooner than other nodes. We may also be interested in how often or with what level of certainly a node receives a given bit of flow. It should be noted that both of these flow outcomes are fully defined within the model but are not necessarily the empirical outcomes that we actually measure. What we do in network research is equate these model outcomes with other constructs such as the likelihood of getting a job (Granovetter 1973, 1974), being promoted (Brass 1984, 1985; Burt 1992), or being creative (Burt 2004; Perry-Smith 2006). These flow outcomes (time until arrival; amount of non-redundant flow received) are then related to a variety of more general outcomes, such as creativity, likelihood of promotion, getting a job, etc.

We emphasize three points based on this discussion. First, network theory based on the flow model assumes that flows are what is theoretically essential, but is also what is not measured. What flow theory consists of is a set of machinery for examining the observable network of social relations among a set of actors and inferring the latent flows that we regard as the key determinant of important outcomes. If the flows were directly measurable, we would not need to infer that nodes with more structural holes (or weak ties) would receive more information: we would simply measure the information they got.

Second, network theory based on the flow model depends on the relative permanence of ties. For example, consider a node that profits from being the broker between otherwise unconnected nodes. This works only if the spanned nodes cannot simply create a tie with another at will. If a direct tie can always be formed, the importance of paths through a network vanishes, as does the importance of structure in general.

Third, when researching the exploitation of network position by nodes, it is problematic to measure relational *events* such as interactions and flows rather than relational states, because power use can change the event network. For example, if a node tries to extract rents for being between two others, the others may choose a different path (Ryall and Sorenson, 2007; Reagans and Zuckerman, 2008). So the event network we see is not the potential structure defined by underlying relations, but an actualized instance that could change at any time and therefore does not tell us what other paths might have been possible.

Refining the Flow Model[12]

By specifying additional features of the central process in the model, we can generate additional theoretical implications. For example, for the flow model, we can specify different variations for how flows move through the network. These can then be compared and contrasted in order to elicit dimensions along which they differ. Finally, the dimensions are used to categorize these and other flows. We consider each of the

[12] This discussion is drawn from Borgatti (2005)

following different kinds of traffic: used goods, money, gossip, e-mail, attitudes, infection, and packages.

Used Goods. Consider the case of a used paperback novel that passes from person to person, particularly through the mails. The novel is a solid, indivisible object that can only be in one place at a time. As it goes from person A to person B to person C etc., it could easily return to a person earlier in the chain, simply because person G has no idea that person B had previously received it, and person B then graciously passes it on to someone else. However, except in special cases (e.g., Alzheimer's), the book does not pass via the same link more than once. That is, if B has sent it to C, and later B receives the book again, he or she will not normally send it to C again.

Hence, the paperback traverses the network using what graph theorist would call a trail – a sequence of incident links in which no link is repeated. Trails are distinguished from paths – sequences in which not only links but also nodes cannot be repeated – and walks, which are unrestricted sequences. All paths are trails, and all trails are walks, but not every walk is a trail and not every trail is a path.

Money. Consider a specific dollar bill that moves through the economy, changing hands with each economic transaction. Like the gift, the dollar bill is indivisible and can only be in one place at a time. However, unlike the gift, the dollar bill is not proscribed from passing over the same link more than once. In fact, it could easily move from A to B, B back to A, A to B again, then B to C, and so on. From a graph theoretic point of view, the bill traverses the network via walks rather than trails. As a result, the movement of money can be modeled as a Markov process.

Gossip. Imagine a juicy, very private, story moving through the informal network of employees of an organization. The story is confidential, which does not impede its flow, but means it is typically told behind closed doors to just one person at a time. Unlike gifts and dollar bills, the story can be in several places at once. It spreads by replication rather than transference. Like gifts but unlike dollar bills, it normally does not pass the same link twice (i.e., I don't tell the same person the same story), but can pass the same node multiple times. Thus, it traces trails through the network rather than walks.

E-mail. A typical example is an email message that warns of an electronic virus. The message is forwarded from one person to several of his contacts, often by sending one message to all of them simultaneously (unlike confidential gossip). The message exists in multiple places at the same time, thanks to diffusion by replication.

Attitudes. Here the notion is of an influence process in which, through interaction, individuals effect changes in each others' beliefs or attitudes. Thus, attitudes about what fashion items are "in" versus passé are spread from person to person. The attitudes spread through replication rather than transfer (I don't lose my attitude the moment I infect you with it). A speaker may persuade many people at the same time, and the trajectories followed by the attitude can revisit links – I can continue to influence you about the same thing over time.

Infection. Consider the case of an infection to which the host becomes immune. The infection spreads from person to person by duplication, like gossip but doesn't re-infect anyone who already has had it because they become immune.

Packages. A package delivery process has the unique characteristic of having a fixed destination or target. In addition, a driver delivering a package normally knows and selects the shortest route possible, so that the package's trajectory follows geodesic paths through a network of roads and intersections.

Given these thumbnail sketches, it is not difficult to see a small set of attributes or dimensions along which these different flow processes vary. One attribute has to do with the mechanics of dyadic diffusion: specifically, whether diffusion occurs via replication (copy mechanism) or transfer (move mechanism). Another attribute, applicable only to replication-based flows, is whether the duplication is one at a time (serial), like the passing-on of a paperback novel, or simultaneous (parallel), like a radio broadcast. A third attribute concerns whether the traffic flows non-deterministically, meaning that at any particular juncture traffic always takes the "best" way (such as taking the shortest possible road to a predetermined target), or whether traffic flows in a blind, undirected way. Finally, there is an attribute that describes whether trajectories follow graph-theoretic paths, trails or walks.

The first two attributes both relate to the mechanism of node to node transmission. In addition, the second attribute is not independent of the first, since it is only defined for cases falling into one class of the first attribute. As a result, we can simplify the situation by combining the two attributes into a single categorical dimension with three classes: parallel duplication, serial duplication, and transfer.

Similarly the remaining two attributes are both concerned with the kinds of trajectories that something flowing through the network can take. For convenience, they too can be collapsed into a single categorical dimension that describes the four kinds of trajectories that are realizable. These are geodesics, paths, trails, and walks.

Taken together, these two dimensions can be used to construct a simple typology, as shown in Table 5. In the table, the rows correspond to the trajectory dimension, while the columns correspond to the transmission dimension. The cells of the table correspond to specific flow processes that have been cross-classified by these two dimensions..

	parallel duplication	serial duplication	Transfer
Geodesics	<no process>	mitotic reproduction	package delivery
Paths	internet name-server	viral infection	Mooch
Trails	e-mail broadcast	gossip	used goods
Walks	attitude influencing	emotional support	money exchange

Table 5: Typology of Flow Processes

Once the rules for how things flow are specified, it becomes possible to make predictions about flow outcomes, either through closed formulas or, if necessary, through simulation. For example, it has been shown (Borgatti 2005) that the betweenness centrality formula (see Equation 1) developed by Freeman (1979) gives the expected values of the number of times something reaches a node in a certain flow process (namely, one in which the things flow along shortest paths, and when there are multiple equally short paths they effectively toss a coin and choose between them with equal probability).

$$b_k = \sum_{i,j} \frac{g_{ikj}}{g_{ij}}$$

Equation 1

Where b_k is the betweenness of node k, g_{ij} is the number of geodesic paths from i to j, and g_{ikj} is the number of geodesic paths from i to j that pass through k

The point here is that the importance of a node in a network cannot be determined without reference to how traffic flows through the network. Nodes that are highly central in trail-based processes such as gossip flow need not be highly central in, say, geodesic-based processes such as package delivery. The characteristics of the flow process affect which nodes will receive flows (quickly, frequently and certainly) and which are in a position to control flows. As a result, centrality measures embody theoretical thinking about network phenomena. Based on the flow model, we are in a position to re-conceptualize centrality as a node-level outcome of implicit models of flow processes. More specifically, the formulas for centrality concepts like betweenness and closeness as generating the expected values – under specific unstated flow models – of certain kinds of node participation in network flows. As such, they do not actually measure node participation at all but rather indicate the expected participation if things flow in the assumed way.

Thinking of existing centrality measures as models begs the important question of what exactly they are models of. For closeness and betweenness centrality, there are clear answers. In the context of network flow, the essence of closeness is time-until-arrival of something flowing through the network. The Freeman formula provides expected values of arrival times for package deliveries and other flow processes in which traffic moves along shortest paths or take all paths simultaneously. In contrast, the essence of betweenness is frequency of arrival. As noted, the Freeman formula provides expected values for how often packages pass a station in a package delivery system.[13] Thus, we can see that the essence of measures like closeness and betweenness can be separated

[13] It is worth noting in passing that time until first arrival and frequency of arrival are concepts that are well studied in the context of Markov processes and provide a bridge to that literature.

from the particulars of their formulas which embody the characteristics of the flow processes for which they were designed. A complete typology of centrality measures would therefore include not only the dimensions pertaining to flow characteristics, as in the table above, but also to the aspect of node participation captured (such as first arrival time and arrival frequency).

Finally, a striking fact about the set of centrality measures currently in existence is the absence of measures designed for the flow processes of greatest interest. The Freeman measures which dominate empirical network analysis are largely misapplied since the processes of interest are typically not based on geodesic paths. Thus, there is a real need for new measures that apply to more realistic flow processes. Of course, as this paper has shown, we can use simulation to obtain estimates of the expected values for any flow process. However, simulations are relatively costly and are not suitable for large graphs. Therefore, a crucial next step is the development of analytical solutions – i.e., formulas – for the expected values for arrival times and frequencies for a variety of different flow models, a task that Friedkin (1991) and Newman (2004) have already begun.

7. The Network Coordination Model

While the flow model is the most developed theoretical platform in network theory, it is not the only one. The field has clearly identified phenomena and developed theoretical explanations that cannot be reduced to the flow model. One such area is the study of power. Cook and Emerson (1978) pioneered the experimental study of the exercise of power in exchange networks. In their experiments, subjects occupied nodes in a network designed by the researcher. The subjects played a game in which, at each round, they had the option to negotiate a deal with someone they were connected to. At each round, each subject could only close on one deal. Across rounds, the subjects' objective was to make as many deals at the best possible terms as possible. For example, for the network in Figure 19, Cook and Emerson found that the subject in position B was able to negotiate the best deals, even though subjects were not shown the structure of the network they were embedded in. From Cook and Emerson's point of view, the fundamental advantage that B enjoys is the dependency of others, which is a function of the (lack of) availability of alternatives on the part of B's potential partners. Node B has two alternatives available for making a deal, while A and C have no alternatives to B and are therefore wholly dependent on B. This positional advantage is very different from the concept of centrality, which largely emerges from the flow model. This can be seen in the experimental results for the network in Figure 20, in which B and D emerge as high power positions and A, C and E have very low power. This might seem surprising given that B, C and D all have two potential trading partners, but the difference is that C's partners B and D both have better alternatives to C, namely the wholly dependent A and

E. Thus, whereas a basic principle in centrality phenomena is that being connected to well-connected others implies greater centrality, in power phenomena it can be the other way around: being connected to weak others makes one powerful and being connected to powerful others makes one weak (Bonacich 1987; Markovsky, Willer and Patton 1988; Marsden 1983).

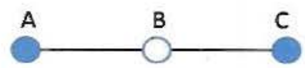

Figure 19: Experimental exchange network in which node B has the most power

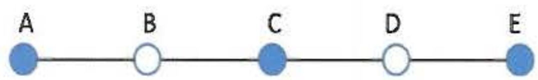

Figure 20: Experimental exchange network in which nodes B and D have the most power

What is especially interesting about network power is that network structure (and location within that structure) matters, and yet the basis for network power is not the accumulation or early reception of a resource that is flowing over well-positioned nodes, as it is in the flow model. This is especially clear in the experimental setting because the rules of the game explicitly prohibit the flow of resources. Nor is power itself flowing, since, if it were, nodes adjacent to a powerful node would be empowered.

Another way to look at network power is in terms of coordination and virtual amalgamation. Consider a node E negotiating with a set of alters A1 through A4, as shown in Figure 21. Since there is only one E and several of the A, one might expect E to have a difficult time. But this would only be true if the A's worked together as a unit. One way this can happen is if the A's are bound together by ties of solidarity. In the extreme, this can be seen as converting the A's into a single node that can deal with E on an equal basis – i.e., a mechanism of virtual amalgamation as shown in Figure 22. This is the principle behind unionization.

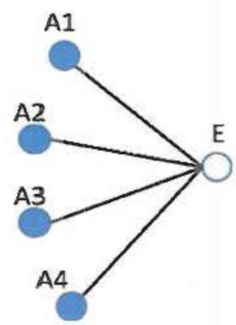

Figure 21: Negotiation network

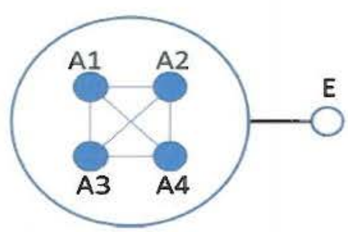

Figure 22: Negotiation network with the unionization of A's

A closer look at the unionization example suggests that two kinds of relationships among nodes are implicit. One is the potential exchange tie that exists between E and its alters. The other is the solidarity ties that may exist among the alters. A key point is that the alters in Figures 21 and 22 are essentially of a type, with the same interests (e.g., to exchange with E) and capabilities (making them interchangeable from E's point of view).

This effectively allows E to induce competition (itself a kind of tie) between the A's (which can be mitigated by ties of solidarity, as in unionization).

A different sort of case is the so-called "network organization", in which a set of autonomous organizations coordinate closely, as if comprising a single, superordinate entity (Jones, Hesterly, and Borgatti 1997; Powell 1990). By working together they can accomplish more than they could alone. We can view this phenomenon as virtual capitalization, meaning that the bonds between the nodes enable them to act as if they were transferring the capabilities of the other nodes to each other, but without actually doing so. Supply chain networks have a similar character. Rather than vertically integrating and taking on the tasks and abilities of upstream suppliers (as in the simple capitalization process that occurs in the flow model), the firm has bonds with those suppliers that enable it to behave as if it had those capabilities. More generally, this is the same phenomenon studied by principal/agent theory, in which the agent acts in the interests of a principal without the principal having to do the work themselves.

In all of these examples – from exchange experiments to principals and agents – a common underlying theme is that the network tie serves as a bond that aligns and coordinates action, enabling groups of nodes to act as a single node, often with greater capabilities. In the case of experimental exchange networks, when a pair of nodes makes a deal in a given round, they become, momentarily, a unit that excludes those not part of the deal. From this perspective, a node's advantage derives from its inexcludability. For example, consider the positions of B and D in Figure 20, if C and D make a deal, B can make a deal with A. If D makes a deal with E, then B can make a deal with either A or C.

There is no combination of outcomes in any round that does not give both B (and its twin, D) the option of making a deal.

Like the flow model, the coordination model permits a number of derivations which in turn enable us to construct measures of power and predict power-based outcomes. For example, the logic of dependency and excludability dictates that the existence of node A on the other side of node B is detrimental for node C, who would rather B not have any alternatives to itself. Generalizing this a bit, paths of *even* length emanating from a node reduce its power, whereas paths of *odd* length increase its power. This theorem is the basis for several measures of network power, including GPI (Markovsky et al., 1988) and beta centrality (Bonacich 1987, 2007).

The GPI measure is described by Markovsky et al (1988) as follows: "The procedure for determining GPI involves counting path lengths. Thus, network B-A-C has two one-paths, A-B and A-C. B and C are linked by a two-path. As explained below, path counting is greatly simplified by only counting the number of nonintersecting paths of each length stemming from a given position. Nonintersecting paths stemming from position X have only X in common. In Figure 2, for example, three nonintersecting two-paths stem from D, but only one nonintersecting two-path stems from El (connecting with either EZ or E3). An implication of this procedure is that it does not matter for X whether a position m steps away "branches" to one or a hundred positions m + 1 steps away. All that matters is whether or not there is a position m +1 steps from X. It may now be apparent that X's odd-length nonintersecting paths are advantageous, and even-length nonintersecting paths are disadvantageous. Advantageous paths either provide direct exchange alternatives (in the case of one-paths), or counteract the advantage-robbing effects of disadvantageous paths. The GPI simply tallies the number of advantageous paths and subtracts the number of disadvantageous paths to determine each position's potential power.

Similarly, Bonacich's (1987) beta centrality/power measure is defined as the total number of direct and direct walks from a node to all others, weighted inversely by their length,

$$c(\alpha, \beta) = \alpha \sum_{k=0}^{\infty} \beta^k R^{k+1} 1 = \alpha(R1 + \beta R^2 1 + \beta^2 R^3 1 + \ldots).$$

where R is the adjacency matrix of the network and alpha and beta are parameters.

In the equation, the parameter beta is assumed to be negative, making the number of even-length paths count against a node's power and the number of odd-length paths count towards their power.

Another derivation from the bond model is that isomorphic nodes will have similar outcomes, even if they are not reachable from each other (as flow-based processes would require). For example, in Figure 23, nodes A and H are structurally isomorphic, and therefore must have the same structural advantages and disadvantages. Holding constant individual differences in the abilities of actors occupying network positions, we can expect that structurally isomorphic nodes will have similar outcomes.

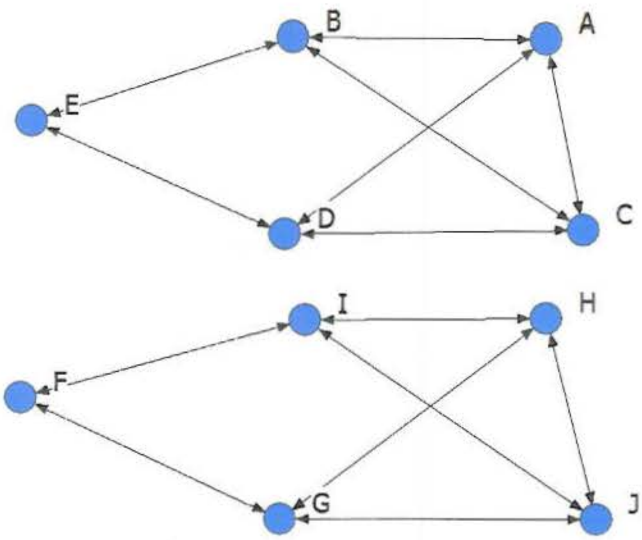

Figure 23: Nodes A and H are structurally isomorphic

More generally, the work of Everett and Borgatti (1994) on role colorings can be integrated into this framework. They begin by defining a role concept an ecological coloring:

Definition. Let N(u) denote the set of nodes that u is adjacent to. Let C(u) denote the color of a node and let C(N(u)) = {Union C(u): u an element of N(u)} represent the set of colors associated with u's neighbors. Then a coloring C is ecological if for any pair of nodes a and b, C(a) = C(b) if C(N(a)) = C(N(b)).

According to the definition, a coloring is ecological if every node's color is entirely determined by the colors of its neighbors. Consequently, if a node u is surrounded by red and blue nodes only, and another node u is also surrounded by red and blue nodes only, then u and L' must be colored the same.

The appellation 'ecological' is meant to suggest a coloring in which the environment of a vertex determines something about the vertex. Ecological colorings are useful in formalizing sociological theories in which the environment of an actor is thought to shape that actor. For example, in organizational theory, population ecologists (Hannan and Freeman 1977; Aldrich 1979) hypothesize that organizational forms are determined, through natural selection and adaptation, by their environments, which consist largely of other organizational forms. Similarly, in biology, it is commonplace to attribute features of a species' morphology to its relations (who eats whom, who shares resources with whom) with other species. The ecological view is also prevalent in network theories of attitude formation (Erickson 1988) and diffusion of innovation (Burt 1987). In fact, it is fundamental to all views of contagion (Burt 1992) that are based on concepts of spatial autocorrelation (Cliff & Ord 1973). For example, Burt (1991) models an actor's attitude as a linear function of the average of the attitudes of those connected to the actor. Thus, two actors surrounded by the same combination of attitudes are predicted to have the same attitudes as each other.

We hypothesize that the partition of nodes according to power forms an ecological coloring:

Proposition 1. Let P be a power coloring of an exchange network in which all nodes are allowed an equal number of exchanges. Then for all a, b, $P(a) = P(b)$ if $P(N(a)) = P(N(b))$.

One shortcoming of the ecological coloring is that it captures only half of the intuitive notion that power is a function of the power of anode's neighbors. In an ecological coloring two nodes with the same power neighborhoods are required to have the same power, but the converse need not be true. That is, several nodes could be assigned the same color, yet have radically different neighborhoods. An example is given by the coloring in Fig. l(i) which assigns the same color to all peripheral nodes, and a different color to the central node. The coloring is ecological since every pairs of nodes surrounded by the same colors are colored the same. But consider the neighborhoods of the greens. Two of the greens have both a green and a red in their neighborhoods, while the other has only a red. If colors correspond to power levels, this would mean that nodes could be equally powerful, yet be surrounded by very different 'power environments'. The converse of an ecological coloring would require that any two nodes assigned the same color have the same colors in their neighborhoods. This coloring is well known in the network role literature as regular equivalence (White and Reitz 1983; Borgatti and Everett 1989;Everett and Borgatti 1991). It is defined as follows:

Definition. A coloring C of a graph G(V, E) is regular if for all a,b elements of V, C(a) = C(b) implies C(N(a)) = C(N(b)).

A comparison of these two definitions reveals that ecological colorings are in a certain sense opposites of regular colorings. Whereas in a regular coloring the color of a vertex implies a certain combination of colors in its environment, in an ecological coloring it is the colors in the environment which determine the color of the vertex. In some ways, the ecological coloring is easier to comprehend as a model of social relationships. We can easily imagine a process (e.g. attitude formation) by which the kinds of vertices in a particular vertex's neighborhood would tend to shape that vertex into this or that kind. Thus we can see the ecological coloring as the end state of an influence process. In contrast, a regular coloring is more difficult to associate with a social process. If we used the same kind of reasoning as with ecological colorings, we would posit that each vertex exerts an influence on its neighborhood which determines the distribution of colors therein. However, this is hardly plausible since each element in the neighborhood is also a neighbor of several other vertices as well, each exerting their own influence. Hence, a regular coloring requires positing a larger, network-wide force which simultaneously structures the patterning of all links. Whereas an ecological coloring may be seen as emerging from the behavior of individual elements, regular colorings must come from the collectivity as a whole. In this sense, ecological colorings are more local or micro in spirit while regular colorings are more global or macro.

Both notions fit our intuitive understanding of the social concept of role. A named social role such as 'doctor' or 'mother' carries with it a set of relationships with other roles that every actor playing the role is expected to have with individuals playing reciprocal roles. For example, we are unpleasantly surprised when we find a doctor that does not heal patients or a mother that does not care for her children. This understanding is consistent with the notion of a regular coloring. At the same time, we expect that if an individual's relationships with others are identical to those expected for a given role, then they can be considered to be playing that role. For example, if a person takes on all the duties of a teacher with respect to a set of students, it would be hard to avoid recognizing that they are playing the role of teacher. This understanding is consistent with an ecological coloring.

While ecological and regular colorings may be opposites in a certain sense, many colorings are both ecological and regular. We call such colorings perfect. They may be defined as follows:

Definition. A coloring C is perfect if C(a) = C(b) iff C(N(a)) = C(N(b)).

According to the definition, a coloring is perfect if it is both regular and ecological. That is, vertices with the same color environments are themselves the same color, and vertices of the same color have the same color environments.

Based on experimental evidence in exchange networks, it is speculated that power partitions in networks form perfect colorings (Borgatti and Everett, 1992; Borgatti and Everett, 1994).

8. Goals of Network Theory

In the *Fundamentals* chapter of this report we that there are two basic types of outcomes that network analysis has devoted itself to. The first is node homogeneity – similarity of nodes in terms of attitudes, beliefs, behavior, and, in the case of collective actors like firms, internal structure. The second is node (or network) achievement, including performance and rewards. This type of work is generally known as the social capital literature. Combining these two generic outcomes with the two explanatory models we have outlined, we get a simple typology of network theorizing.

	Achievement	**Social Homogeneity**
Network Flow Model	Capitalization	Contagion
Network Bond Model	Cooperation	Convergence

Table 6: Network functions (mechanisms) by model and research tradition.

As shown in Table 6, the top right quadrant consists of flow-based explanations of homogeneity (termed Contagion), which is a well-populated segment of the network literature. The principal example of this kind of work is diffusion or adoption of innovation studies in which nodes are conceptualized as influencing each other to adopt their traits. Studies of this type seek to explain shared attitudes, culture and practice through interaction (e.g., Davis, 1991; Geletkanycz & Hambrick, 1997; Harrison & Carroll, 2002; Haunschild, 1993; Krackhardt & Kilduff, 2002; Molina, 1995; Sanders & Hoekstra, 1998). The spread of an idea, practice or material object is modeled as a function of interpersonal transmission along friendship or other durable channels. Ties are conceived of as conduits or roads along which information or influence flow. Seen from the point of view of the group as a whole, actors are mutually influencing and informing each other in a process that creates increasing homogeneity within structural subgroups. The ultimate distribution of ideas is a function of the structure of the underlying friendship network. Seen from the point of view of a single actor, her adoption of a practice is determined by the proportion of nodes surrounding her that have adopted, while the timing of adoption is a function of the lengths of paths connecting her to other adoptees. Work on communities of practice (e.g., Wenger, 1998) fits this category, although researchers in that field resist "reduction" to network terms and use terms like mutual engagement and interaction instead of network ties.

The bottom right quadrant contains coordination or bond-based explanations of the same thing (termed Convergence). This is an under-populated area that sees homogeneity as a special case of coordination in which nodes behave similarly rather than simply in concert, similar to the sociological concept of gemeinschaft (Tönnies 1887). Work in this area includes the networks as prisms concept of Podolny (2001), along with the empirical work of Kilduff and Krackhardt (1994) and identity-based network research of Podolny and Baron (1997) and Halgin (2009) which suggests that network ties provide informational clues to audiences regarding the quality and identity of an actor. In addition, studies of this type seek to explain common attitudes and practices in terms of similar network environments, usually conceptualized as centrality or structural equivalence (e.g., Galaskiewicz & Burt, 1991). Actors are structurally equivalent to the extent they are connected to the same third parties, regardless of whether they are tied to each other (Lorrain & White, 1971). A classic paper in this vein is Erickson's(1988) use of structural equivalence to explain common attitude formation. Similarly, DiMaggio and Powell (1983:148) and DiMaggio (1986:360) use measures of structural equivalence to model the notion of organizational isomorphism. The mechanisms generating similarity between two organizations have to do with sharing the same environments and/or recognition of each other as appropriate role models. In general, studies in the tradition of institutional theory fit here.

The top left quadrant contains pipe or flow-based explanations of achievement (termed Capitalization). Work in this area is exemplified by strength of weak ties theory, as well as the information benefits theory of structural holes. These studies comprise the connectionist flavor of social capital studies. In these studies, an actor's success is a function of the quality and quantity of resources controlled by the actor's alters (e.g., Anand & Khanna, 2000; Koka & Prescott, 2000; Oliver, 2001; Stuart, 2000). Ego's ties with alters are conduits through which ego can access those resources. Different kinds of ties have different capacities for extracting resources (Borgatti & Cross, 2003). As with structural capital studies, actors are typically seen implicitly as rational, active agents who instrumentally form and exploit ties to reach objectives. Most studies of this type are focused on the individual, and are often based on ego-network data alone. Research in the stakeholder and resource dependency traditions can fit here, particularly when the work portrays an actor as actively trying to co-opt those with whom it has dependencies.

The bottom left quadrant consists of coordination or bond-based explanations of achievement (termed Cooperation). This is exemplified by the stream of research on experimental exchange networks (Bonacich 1987; Cook and Emerson 1978; Markovsky et al., 1988), as well as the control benefits theory of structural holes (Burt 1992). These comprise the topological or structuralist variant of social capital studies. At the actor level, these studies focus on the benefits to actors of either occupying central positions in the network (e.g., Brass & Burkhardt, 1993; Powell et al, 1996) or having an ego-network with a certain structure (e.g., Burt, 1992; Burt, 1997; Burt, Hogarth, & Michaud, 2000; Coleman, 1990). The actor is typically seen as a rational, active agent who exploits her position in the network in order to maximize gain. The actor's position in the network is described in terms of a desirable abstract pattern of ties, such as having a sparse ego-network or being located along the shortest path between otherwise unconnected actors. The benefits to the actor are principally a function of the topology of the local network, and ties are implicitly conceived of as forming a leverageable structure (Markovsky et al, 1993). At the network level of analysis, structural capital studies seek to relate the network structure of a group to its performance (e.g., Athanassiou & Nigh, 1999). This kind of study is one of the oldest in social network research, with dozens if not hundreds of exemplars, starting with the work of Bavelas (1950) at MIT, who investigated the relation between centralization and group performance (see the review by Shaw, 1971).

9. Discussion

In this section, we comment more generally on issues in network theorizing and some of the benefits of our approach.

Mathematizability

A key observation about network theory is that the core concept of the field – the network – is not only a sociological construct, but a mathematical object. As a result, it is sometimes possible to use the machinery of mathematics to generate new theory. For instance, Rapoport (1963) and others showed that transitivity tends to create highly clustered graphs that have many long paths or have disconnected components, which means that networks with high transitivity are slow or incomplete diffusers. This, of course, is the basis for SWT and SH theory. More generally, the coincidence of sociological networks and mathematical networks makes it easy to generate formal theory that is expressed in mathematical form. This is an important blessing that over time will have an important impact on the ability to use network theory in practical applications. That is, it seems clear it will eventually be possible to generate software systems to simulate network processes.

On the negative side, the dual nature of the network construct also carries with it the danger that the non-mathematically inclined will not see it as theory at all, but rather as some form of statistics. A good example is the notion of betweenness centrality, which is defined by the formula shown in Equation 1. As noted above, it has been shown (Borgatti 2005) that the betweenness formula gives the expected values of the number of times something reaches a node in a certain flow process (namely, one in which the things flow along shortest paths, and when there are multiple equally short paths they toss a coin and choose one of them with equal probability). Thus, what looks like methodology is in fact formal theory based on the flow model.

It is worth noting that even things as technical as the notions of structural equivalence (Lorrain and White 1971) and regular equivalence (Everett and Borgatti 1994; White and Reitz 1983) were explicitly developed in an effort to formalize the social role theory of Linton (1936), Nadel (1957), Merton (1959) and others. Similarly, the notions of clique (Luce and Perry 1949), n-clique (Luce 1950), k-plex (Seidman and Foster 1978) and other subgroups, which sound so methodological, were actually attempts to state with mathematical precision the concept of group which Cooley (1909), Homans (1950) and others had discussed at a more intuitive level.[14]

Model- based theorizing

In this report, we have argued that at least some portions of network analysis can be described as *model-based theorizing*, and have outlined two fundamental models, the flow and bond models, that underlie extant network theorizing. According to Lave and March (1975), model-based theorizing is one of the strongest forms of theorizing. In model-based theorizing, we imagine an observed state of affairs as the outcome of an unseen process which is what is specified by the model. Given the model, you can derive testable implications, including the original observations that led you to postulate the model. Ideally, a model can also be expressed formally so that the machinery of

[14] An explanation of these terms is beyond the scope of this article. For a review, consult Wasserman and Faust (1994)

mathematics and/or simulation can be used to derive additional implications that might be difficult to develop by simple intuition (e.g., Everett and Borgatti 1994; Lorrain and White 1971; Luce and Perry 1949; White and Reitz 1983). The implications are used to test the theory, as well as to apply the theory to new situations.

One feature of model-based theorizing is the separation between the abstract elements of the model, and the mapping of those elements to the real world. Hence, we should write network theory at the level of, say, the function of enabling something to flow from one node to another, not at the level of, say, who-likes-whom ties. For example, in SWT, Granovetter (1973, p 1361) specifies quite clearly what a strong tie is (namely a combination of time, emotional intensity, intimacy, and reciprocal services). However, this definition is open to debate and is not appropriate in all settings, such as when the nodes are firms. However, a closer look at the theory shows that a specific definition is actually unnecessary: any type of tie that has the property of generating g-transitivity will do. The rest of the theory does not make use in any way of the fact that strong ties were defined in terms of emotional intensity and the rest. The only property of strong ties that is actually utilized is the property of g-transitivity.

There is an analogy here to object-oriented computer programming (OOP), in which real-world entities are modeled as classes of "objects" which consist of data along with procedures (called "methods") that operate on them. A key principle of OOP is that one should program to an interface rather than an implementation. What this means is that higher level code should not have to know the details of how lower level code works – the functions of the lower level code should be encapsulated so that higher level code deals only with the functions of the code, not the means by which they are accomplished.

For example, if we are modeling interactions among animals, our main code should not have to know how, exactly, a cow sounds or a dog moves. Rather, it should be able to issue to the object representing a particular animal a general command such as "make sound" or "move" and have this interpreted appropriately by the object, which knows how to make its own sound and how to execute its own way of moving. In this way, any changes to how a specific kind of animal makes sounds or moves will not affect the main program, and new types of animals can easily be incorporated.

In network theory, the concept corresponding to OOP's object is the network, and what corresponds to OOP's methods is the set of processes or functions that we define on the network, such as flow of information. In our view, this analogy helps point the way toward dealing with issues of context and culture. For example, a theory built on a particular definition of tie (e.g., friendship) will run into problems when we try to apply it cross-culturally, since friendship has different implications in different cultures and settings. A better approach is to build theory at the level of abstract ties which have certain properties needed by the theory (e.g., ties create shared identity, or ties transfer resources). Then to apply the theory in a given setting, we use our situated ethnographic knowledge to find an appropriate specific type of tie that, in that context, entails the functions needed by the theory.

The analogy also helps clarify the question of whether we can apply the same network theories to collective and/or non-human actors – such as firms – as we do to actors that are individual persons (Madhavan 2010). For example, if we wish to apply SWT theory to firms, we need only ensure that the kind of ties we study have the property of g-transitivity and serve as pipes through which resources flow. We needn't worry that ties among firms don't have "emotional intensity" or "intimacy" as long as there is a kind of inter-firm tie that has the two properties that Granovetter's model depends on – namely, transitivity and enabling the flow of information. Of course, it should be noted that different kinds of nodes have different capabilities, which needs to be taken account of in generating the auxiliary theorizing that links model outcomes to such outcome variables as, say, performance or creativity. For example, when an individual hears two bits of information he has a fighting chance of integrating them, but when a firm hears two bits of information it may be different parts of the organization that house them and the bits may never come together in the same space to be integrated.

Endogeneity

In this report, we have separated network theory from theory of networks, which makes sense analytically. However, it also raises some questions. First, there is the question of whether the distinction is "merely" analytical since it might be expected that, in reality, the two kinds of processes occur together. Second, there is the concern that we cannot correctly predict outcomes of network structure if we haven't taken account of how the network got there – i.e., the trajectory of events matters. Third, there is the question of endogeneity. Endogeneity means different things in different contexts, but one sense of the term is that factors seen as causing the outcome are in some part dependent on the outcome. Finally, the issue of agency comes to mind. If actors deliberately shape the networks around them for their benefit, can it really be said that it was network structure that led to the benefit?

To begin our discussion, let us make clear on a semantic level that network theory and theory of networks are not disjoint sets. Recall that we defined the domain of network theory to be the consequences of network processes and structures. In our examples, these consequences were things like performance or reward. However, it is obvious that the consequences of network processes can include other network phenomena, in which case network theory is simultaneously theory of networks, which is to say we have a *network theory of networks* (see Table 7). In a network theory of networks, both independent and dependent variables involve network properties. An example is the cascade of effects that can be produced by the formation of a positive or negative tie between two actors. For instance, suppose spouses Bill and Nancy develop a negative tie between them, culminating in an acrimonious divorce. According to balance theory, we can expect that a third person, Sally, with a strong positive tie to both parties will experience stress, and will be likely to weaken the tie with one of them -- i.e., choose sides. This in turn has a ripple effect on Sally's friends, who may also weaken ties with Bill. Another example is the interaction between homophily and centrality (Ibarra, 1992). If actors have a marked tendency to be homophilous with respect to race, and one race has a clear numerical majority, we can expect that members of the majority race will be more central.

		Dependent Variable	
		Non-network variable as outcome	**Network variable as outcome**
Independent Variable	**Non-network variable as antecedent**	(Non-network theory)	Theory of Networks
	Network variable as antecedent	Network Theory	Network Theory of Networks

Table 7: Network theory and theory of networks

A more interesting question is whether, as Salancik (1995) seemed to feel, a network theory must include a theory of networks. In particular, are there any circumstances where we must take into account how a network reached a given structure in order to understand the consequences of that structure? Common sense would suggest "yes". For example, consider two nodes who occupy identical positions in a network (both have many structural holes), and have similar motivations. However, node A reached that position through a long campaign of strategic relationship-building, while node B arrived at it serendipitously and in fact is unaware of the potentialities of its position. We can readily imagine that, in a population of nodes like A, the correlation between structural holes and power will be higher than in a population of nodes like B, who don't think to exploit their position. Thus, the causal link between holes and power varies depending on how the nodes got their holes. Or does it? The key difference between A and B is that A's journey to that position implies awareness of its value, allowing A to exploit it. But suppose there other ways of becoming aware of the value of one's structural holes. For example, suppose node B attends an executive education class on social network analysis. Given that B has the same position and same awareness as A, shouldn't the consequences for B be the same as the consequences for A, all else being equal?

Thus, on closer inspection, the answer to whether network theory must include theory of networks, would seem to be "no". If a model has been constructed that embodies the mechanisms which convert a given set of inputs at time T to an output at T+1, then given that input nothing else is needed to explain the outcome. In practice, however, it is a little more complicated. For one thing, knowing the input at T may involve a longitudinal analysis. As a very simplistic example, suppose an outcome is a function of whether a network is increasing in density, or decreasing (e.g., the nodes make certain choices when they perceive the density to be on the rise). A snapshot of the network at a single point in time doesn't tell us whether the density is waxing or waning. However, once we have determined, via longitudinal analysis, whether it is waxing or waning at time T, we can set the "momentum" variable at T to the observed value, and we now have all the information we need to understand what happens next.

As a more substantive example, consider the strength of weak ties theory. An appealing feature of the theory is that it spans both the theory of networks domain and the network theory domain. As discussed, a key premise of SWT is that networks form in such a way that they exhibit g-transitivity. It can then be derived that bridging ties are unlikely to be strong ties. This is the 'theory of networks' portion of the theory. If we then combine another premise (that bridging ties are the most likely source of novel information), we can conclude that the structural property of having many weak ties is likely to be associated with access to more novel information, which in turn may be associated with performance gains. This is the' network theory' portion. The combination of the two portions is both satisfying and elegant. But do we need the first part to get the second part right? Strictly speaking, the answer is "no". In order to derive the hypothesis that weak ties will be associated with strong performance and that this is mediated by access to novel information we do not need to know why networks have g-transitivity, merely that they do.

On the other hand, there is also the matter of the satisfyingness of the theory. In any theory in which X leads to Y, we can wonder what leads to X. In some cases this feels like an urgent and necessary question. For example, if the explanation for 'why do people divorce' is 'because they want to', we are likely to demand an explanation of why they want to. In other cases, there is enough of a sense of process or mechanism in the theory that we are willing to back off of the chain of infinite regress. For example, among other arguments, Granovetter (1973) uses balance theory to explain g-transitivity. According to balance theory, a person seeks to be congruent with those she likes. When she is not, she feels dissonance, and seeks to reduce it. We could ask why, but most of us in the management field are willing to let that one go and let the psychologists deal with it. Ultimately, at what point we feel enough explanation has been given to be satisfying in a given context is a question for the sociology of science and not a question about a particular field, such as network theory.

It should be noted that the ability, in principle, to theorize about consequences of networks independently of antecedents does not absolve the field from resolving issues of endogeneity in a given empirical inquiry. For example, Lee (2010) finds that in a biotech setting, the cross-sectional correlation between structural holes and innovative performance disappears when controlling for inventors' past performance. Thus, in that particular case, it appears that it is performance that creates holes rather than the other way around, and whatever is responsible for performance is stable over time, so that past performance predicts future performance. Thus it could be an individual characteristic such as skill or personality that causes both structural holes and performance. This is an important result, but should not be misread as saying something fundamental about network theorizing. In every field study we must be concerned about whether A causes B, or the other way around, or both are caused by an uncontrolled third variable.[15]

Finally, we take up the issue of agency as it relates to endogeneity. One of the legacies of the social capital approach in social network research is the notion that ties and position can be "good", i.e., associated with positive outcomes such as performance or reward. Inevitably, this leads to the following bit of reasoning: If occupying a certain position in the network is rewarding, we can expect actors to take steps to achieve that position. Thus, the network structure is not a given in the sense of an exogenous variable, but rather shaped by the actors specifically in order to achieve the very outcomes that we researchers associate with those structures. Therefore, any theory of social networks must take into account actors' agency in creating those networks. The problem with this, as we have pointed out, is that it is not the actors intentions and actions leading to occupying a certain position that creates the outcome but the actual occupation of the position. A rock dropped from the same place in the same way has the same outcomes regardless of whether it was dropped on purpose or by accident. Given the same conditions, the outcomes are the same.[16]

One thing this discussion highlights is the importance of node attributes and contextual factors in network research. Occupying a certain structural position carries certain potentialities, but the actual outcomes may depend on a number of additional

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[15] Note that the possibility that A and B both cause each other should not concern us: if our theorizing suggests that A causes B, and we find that A and B cause each other, then our theory was supported. The fact that we have also learned something about the causes of A is a side benefit.

[16] It might be argued that this is not true in a court of law, where the consequences for the rock-dropper may differ depending on the court's perception of the dropper's intentions. But then the conditions are not the same. From the point of view of the law a rock dropped by accident versus with intent to kill are two different events.

factors, including how the actor plays it. How they play it may be a function of how they got there, and so knowing how they got there could give our predictive ability a boost. However, it is not the journey itself that is the theoretical variable, but rather the complex of conditions (e.g., state of mind, skills, motivations) at the end of the journey creates that is the causal agent. If we can measure that condition directly, there is no need to code the journey. In this sense, if we find that we cannot predict how X leads to Y without knowing how X came about, it is evidence that our theory of how X leads to Y is incomplete: we are missing a node attribute or other contextual factor that interacts with network position to bring about the outcome being modeled.

10. Summary and Future Work

The purpose of this project was to examine the possibility of integrating the seemingly diverse forms of network theorizing into a generic platform from which more specific theories could be derived to tackle particular problems. This is an important goal because the proliferation of network research makes it difficult for practitioners to understand which of the different variants of so-called network theory is relevant to a given problem. Moreover, variants of network theory sometimes employ different mechanisms and make different theoretical assumptions and can therefore produce inconsistent predictions when applied to a given problem.

To address this issue, we undertook an exhaustive review of the inter-disciplinary literature on social networks with an eye towards identifying the distinctive forms of network theorizing. We found that although network theory cannot be synthesized into a single self-consistent theory, there are some large "chunks" of network theorizing that can be collapsed into two major conceptual models, which we have described above as the flow model and the coordination model. Specific theories that are part of a model can be integrated and used to generate specific predictions. The integration of theories across these two models is not possible as the models make starkly different assumptions and employ different causal mechanisms. Drawing on principles from object-oriented programming, we identified, for each of the models, a core logic that is expressable mathematically and that can be combined with a set of auxiliary ideas that can be thought of as an interface that ornaments the basic model and allows for application to different real world problems.

Funded as a Basic Research grant, the goal of our project has been to develop an integrated network theory rather than solve an applied problem. However, it is clear that the big next step is to translate this work in such a way that it can be brought to bear on the specific problems of interest to the DTRA. In the past, one of the problems in applying academic social research to Dept of Defense problems has been how to adjust for the different contexts involved. For example, do the results from psychology experiments on US undergraduates apply to the mentalities of foreign terrorists? A key contribution of our work has been to separate the underlying abstract model embedded in network theories from the contextually situated interface theory that is used to tie the model elements to real world variables. In principle, this effectively makes network theorizing portable across contexts.

At present, however, making the translation to a specific context in order to solve a problem in DTRA's area of interest requires an expert in both network analysis and the subject matter area. Much work needs to be done to develop a standard, widely usable, process for applying the abstract network theory models developed here to varied concrete problems. This is outside of the scope of the present project, but it is worth pointing to the outlines of at least one such process.

For example, in applying network theory to new contexts, one thing that needs to be done is to consider the abstract class to which the outcome of interest belongs. In this project, we have identified two major classes of dependent variables, namely achievement (e.g., performance, success) and homogeneity (e.g., similarity in attitudes, behavior, internal characteristics). So the first thing we do is identify whether the problem of interest is something like who will become a leader of an adversarial group (category: achievement) or which countries will seek to emulate Pakistan (category: homogeneity). In this project we have also considered two major models for how networks work -- the pipes or flow model, and the bonds or coordination model. Both imply social processes that will be at work in producing the outcome of interest. For example, the success of an individual in gaining leadership of a terrorist group will be in part a function of the resources (especially information) that their position in the group's network affords them. The kinds of ties they have with others will determine the size of the pipes that carry resources from others to them. What these resources are and how they flow are all inputs to the flow model. Once these are specified, the machinery of the flow model can be invoked to generate predictions of the relative strength of the different players in vying for leadership. At the same time, the binding and coordinating functions of social ties serve to give actors the ability to get others to do things and act in ways that are beneficial to the actor in question. The machinery of the coordination model works out the relative advantages each actor has with respect to the set of vital functions in the coordination domain. Together, they then yield an estimate of each actor's probability of success.

We envision future work progressing along several fronts. One such line of work would involve the use of mathematical simulations to investigate how the different network models match-up with historical data. How well, for example, can the flow model explain the historical pattern of diffusion of nuclear weapons among nation states? Are there aspects of this historical pattern that call for adjustments of the network models? Another related line of work could use the models we have identified to paint likely possible scenarios for the future. What, for example, are the likely consequences of a nuclear-armed Iran for the countries and groups to which it is connected? Each of the network models we have identified provides a basis for addressing this question in ways that take into account the rich and variegated network topography in which Iran is embedded.

Finally, we believe that there is important work to be done in working out how best to combine the insights of an integrated network theory with other non-relational theories and perspectives, such as those derived from individual and social psychology. In particular, fundamental questions about how what one knows about the structure of the network in which they are embedded influences their ability to manipulate and leverage the network for their own benefit remain unaddressed. We believe that the development of an integrated network theory represents an important advance in the quest to harness the insights of network thinking for purposes of homeland defense. With a plausible candidate for integrated network theory at hand, the focus needs to shift to applying this theory in ways that maximize predictive and explanatory traction in the scenarios of interest to the department of defense.

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APPENDIX A
Research Articles from iAnt Project

1. Borgatti, S.P. and Halgin, D.S. (Conditionally Accepted). "Network Theorizing." *Organization Science*

Research on social networks has grown considerably in the last decade. However, there is a certain amount of confusion about network theory – what it is, what is distinctive about it, how to generate new theory. This article attempts to remedy the situation by clarifying the fundamental concepts of the field (such as the network) and characterizing how network reasoning works. We start by considering the definition of network, noting some confusion caused by two different perspectives, which we refer to as realist and nominalist. We then analyze two well-known network theories, Granovetter's (1973) strength of weak ties theory and Burt's (1992) structural holes theory, in order to identify characteristic elements of network theorizing. We argue that both theories share an underlying theoretical model, which we label the network flow model, from which we derive additional implications. We also discuss network phenomena that do not appear to fit the flow model, and discuss the possibility of a second fundamental model, which we call the bond model. We close with a discussion of the merits of model-based network theorizing for facilitating the generation of new theory.

2. Borgatti, S. & Ofem, B. (Forthcoming). "Social Network Theory and Analysis." (In Press), *Social Network Theory and Educational Change*. Harvard University Press.

3. Borgatti, S.P. and Kidwell, V. (Forthcoming). "Network Theory." In Carrington, P. and Scott, J. (eds) *The Sage Handbook of Social Network Analysis*. Sage Publications

This chapter is about network theory, which in general usage can refer to several different kinds of ideas. For example, both a theory of tie formation and a theory of the advantages of social capital could be considered network theory. In the tie formation case, network properties serve as the dependent variable, and the theory concerns the antecedents of network phenomena. In the social capital case, the network construct is the independent variable, and the theory considers the consequences of network phenomena. We distinguish between the two kinds of theory by referring to the first (on antecedents) as theory of networks and the second (on consequences) as network theory. The focus of this chapter is on network theory, which we define as the proposed processes and mechanisms that relate network properties to outcomes of interest.

4. Mehra, A., Borgatti, S.P., Brass, D., Labianca, G. (2010). "The Social Network Perspective". In Stanley D. Brunn (Ed.) *Engineering Earth: The Impacts of Megaengineering Projects*. Dordrecht, The Netherlands: Springer Science + Business Media.

5. Borgatti, S.P., Mehra, A., Brass, D. and Labianca, G. (2009). "Network Analysis in the Social Sciences." *Science*. Vol. 323. no. 5916, Feb 13, pp. 892 – 895

Over the last decade, there has been an explosion of interest in network research across the physical and social sciences. For social scientists, the theory of networks has been a goldmine, yielding explanations for social phenomena in a wide variety of disciplines from psychology to economics. In this essay, we review the kinds of things that social scientists have tried to explain using social network analysis and provide a nutshell description of the basic assumptions, goals and explanatory mechanisms prevalent in the field. We also give a brief history of network research in the social sciences and identify some historical criticisms and current challenges facing the field. We hope to contribute to a dialogue among researchers from across the physical and social sciences who share a common interest in understanding the antecedents and consequences of network phenomena.

6. Borgatti, S.P., Li, X. (2009). "On Network Analysis in a Supply Chain Context." *Supply Chain Management*. 45(2):5-22.

The network perspective is rapidly becoming a lingua franca across virtually all of the sciences from anthropology to physics. In this paper, we provide supply chain researchers with an overview of social network analysis, covering both specific concepts (such as structural holes or betweenness centrality) and the generic explanatory mechanisms that network theorists often invoke to relate network variables to outcomes of interest. One reason for discussing mechanisms is facilitate appropriate translation and context-specific modification of concepts rather than blind copying. We have also taken care to apply network concepts to both "hard" types of ties (e.g., materials and money flows) and "soft" types of ties (e.g., friendships and sharing-of-information), as both are crucial (and mutually embedded) in the supply chain context. Another aim of the review is to point to areas in other fields that we think are particularly suitable for SCM to draw network concepts from, such as sociology, ecology, input-output research and even the study of romantic networks. We believe the portability of many network concepts provides a potential for unifying many fields, and a consequence of this for SCM may be to decrease the distance between SCM and other branches of management science.

7. Kane, G., Alavi, M., Labianca, G., & Borgatti, S. (Under Review). "Integrating Social Networks and Information Systems: A Review and Framework for Research," 1st revise and resubmit to *MIS Quarterly*.

APPENDIX B
SUNBELT EXPERT INTERVIEW PROTOCOL

- Introduction
  1) Introduce yourself, the LINKS Center, the DTRA project.
- DTRA study objectives
  1) Develop "a broad, generic, adaptable, flexible and modular theory of social networks that spans all relevant disciplines"
  2) "An overarching effort to develop a generic integrated theoretical approach to social networks".
- Grand tour question
  1) "What does network theory encompass? Can you walk me through the different areas that it covers?"
     a) Pick one of their research domains (say, health), and ask, what are the central questions that the field has tried to answer in this area
     b) Pick one of their dependent variables and ask them for another tour of the kinds of explanations people have offered of that dependent variable.
- Distinguishing features
  1) "What do you believe makes network theorizing distinctive?"
     a) Is it more than just relationality? So many theories are relational – is everything network analysis?
        I) If you study "the mother-daughter" relationship, are you doing network theorizing?
- Building blocks
  1) "What are some of the key building blocks of network theorizing?"
     a) *We don't really mean "centrality" or "structural holes", because they are so static, but they are a starting place. We mean themes, favored ways of explaining things, bits of reasoning,* ***mechanisms, processes****:*
        I) E.g., unconnected ties give you non-redundant info.
        II) More links away you are the longer it takes for something to get to you
        III) If you are along the most used path between A and B, you have some potential for gatekeeping, filtering etc.
- Necessary ingredients
  1) "If a generic network theory of everything were possible (or if we could boil network theory down to just a handful of generic theories), what things would definitely need to be in it?"
- Approaches
  1) "How would <u>you</u> go about constructing "a broad, generic, adaptable, flexible and modular theory of social networks"?"
     a) *What work process would you follow to do this?*
- Contrast questions
  1) "Are there areas in social network research that you have noticed are similar to each other but which are not generally seen that way?"

    a) *E.g., the needs of epidemiology are similar to the needs of counter-terrorism: breaking up networks*
    b) *Explore any examples they come up and locate what is similar about them*
  2) "Would you regard Granovetter's SWT and Burt's Structural Holes theory as independent theories, conflicting theories, consistent theories, or as one extended theory?"
- Central disciplinary questions
  1) "What central disciplinary questions have been addressed by network theory?"
  2) "What central disciplinary questions have not yet been addressed by social network theory, but perhaps could be?"
    a) By "disciplinary" we mean basic questions from fields such as sociology, anthropology, psychology etc.
      I) In sociology: the problem of social order. Why do societies hold together?
      II) In organization theory: why do organizations have the forms they have?
- Scope conditions
  1) "What kinds of questions probably can never be addressed by network theory?"
- Obstacles
  1) "What stands in the way of the project goal?" i.e., creating generic module integrated network theory
  2) "Is an integrated theory of networks desirable? Are there negative consequences to doing such a thing?'
- Exit questions
  1) "What else should we be asking?"
  2) "Who else should we be talking to?"

APPENDIX C
SUMMARY OF COMMENTS BY INTERVIEWEES

Person	Prospects for General Theory	Other Observations
1	Don't be too ambitious: middle range theories are preferable: "not so micro that they have no consequences but not so big we lose all this." Grand theory undesirable even if it were possible.	- Identify and test for boundary conditions; simulation is a great tool for this ("we can't figure out how this stuff interacts in the head"). - Identify and critically test import of assumptions - Need greater attention to levels issues, origins, dynamics - Networks don't explain everything—e.g., convincing network theory of "personality" unlikely.
2	Network theory would have a twin focus: (1) "why ties form as they do"; (2) effects of networks on various outcomes (e.g., performance)	- The focus on patterns is what's distinctive in network theorizing. - Pull stuff from existing literature, starting with an enumeration of kinds of ties. Different mechanisms may apply for different kinds of ties. - Perfect prediction not possible

3	"I don't think there is a grand unified theory of everything network. I think there's kind of a metatheory which suggests the elements that should be in a network theory (theories of nodes, ties, dependence). Combination of these may be a network theory. But different domains might require different meta theories. You could have a meta theory that is broad and generic, but each specific domain will require specific adjustments to the theory."	- We probably need a multi-level approach - Take nodes and structure into account simultaneously - More on dynamics - More on origins - Use a problem-centered approach
4	Network theory focuses on relations. It identifies underlying mechanisms (which ones operate when). General theory is possible, but be attentive to the fact that nodes are humans in social network theory.	- Focus on mechanisms: which ones apply when and why? - What is your dependent variable? That should guide your selection of appropriate mechanisms: "A lot of it is driven by the class of things you are trying to explain." - We have to get away from being too descriptive (e.g., physicists studying networks)
5	"Probably both important and impossible." Still, worth trying to pull these various strands together.	- Network theory may not encompass node characteristics, which can be exogenous. - Nodes, crucially, vary in their characteristics. - Context is crucial

Person	Prospects for General Theory	Other Observations
6	Network theory is a theory of relations between components and system; focus on tie, not persons; direct and indirect relations; tie content important but secondary. General theory exists, but must be adapted to particular contexts.	- But must generic theory by taking node attributes and processes into account (stochastic modeling of dynamic networks). - Look at narratives—a la White - Use agent based models - Emphasize dynamic change
7	It is possible to aim at a general theory of networks even if none exists at present. How to do it? Identify menu of ideal-type structures (e.g., core-periphery); then consider causes and consequences of those structures	- Need to inject context into network theories; we have studiously ignored context. - Look at real world for identifying structural ideal patterns of interest; test theory against empirical data - Don't include everything at once: network theory is "terribly simplifying… [need to] deliberately decide which relations are worth considering [for which purpose/outcome]."
8	"Skeptical" that there can be one general theory of networks. It's contingent (on things like environmental munificence). Must consider network theories in context. Also, any general theory must be attentive to underlying mechanisms.	- Context is crucial - What causes dynamic network change: need to know more. - Need a theory that links macro and micro mechanisms - Get at coevolution of actors and networks - A general theory would have to be eclectic (would include ideas that are not traditionally considered the

		domain of network analysis) - Data quality is a crucial consideration - Agency must be considered
9	"I happen to think we have an extremely strong theory [of networks as" pipes" and "springs"]… Most people are unaware of it, or don't think about it at the project level… The strongest theories in every discipline are a combination of theory plus methods and they co-develop"	- Networks and flow we understand well. Need to attend to networks as springs— which require that we get at the mathematics of constraints and enablers - Also need to attend to the state of nodes: node characteristics change over time: state change rarely dealt with, except in simulation work - The govt. should fund a Santa Fe-like institute for research on social networks: that's the best bet for advancement

Person	Prospects for General Theory	Other Observations
10	General network theory focuses on how local level processes accumulate into macro level signatures, and these in turn influence local processes. So, the theory is relevant to all social science. Non-independence of observations: what sets network theory apart from traditional social theories.	- How best to employ network theory depends on what you are trying to explain. - Exponential random graph models: a promising way forward - We need better ways to sample from networks: seldom have the full network - Statistical work + hard data: "any science has to be a marriage between theory, methods, and data." - The theory has to be context specific
11	"There is no network theory. There is a method called network analysis." But that's not to trivialize it—cf. Galileo's invention of the telescope and its ramifications for theory.	- Network methods can be applied across varying contexts, but it works best in conjunction with other disciplinary "background theories."
12	Grand theory of networks may be possible [but mostly we have mid-range theories now]: it would focus on power, affect, structure. It would explain why some networks persist, why others implode, why some change. It is worth trying to come up with such a theory.	- I take a problem centered view of the world: there aren't too many problems that couldn't be fruitfully studied by using social network analysis. - Social network theory needs to be attentive to the peculiarities of humans as nodes.

13	It is possible. Steve's presidential address "is probably in my opinion the best statement to date of the status of theorizing in social networks"	- Theories evolve in response to challenges of data. So, it is an evolving thing. - Network research "infected with hubris." The idea that networks can account for everything is "ridiculous." - Network analysis is metaphorical (ties don't necessarily exist out there): "sometimes we push the metaphor too much" - "you guys are doing the right thing by asking different people what they think." - We need more data to test and improve our theories
14	"I don't think there's any general theory of networks." Exchange networks and power: areas where we have the most fully elaborated network theory.	- Networks focus on structure; they can't explain what happens internally within nodes - Take context into account: "if they're interested in terrorism, then their theories are going to be informed by the characteristics of those networks. "

15	Possible, but our knowledge is limited so far. "We've not done a good job of just knowing the basic structures that exist in networks."	- Agency: Do they do stuff because of their existing network ties? Or do they build network ties to do stuff? - Need to better understand the macro-micro link - Need deeper understanding of network evolution - "Networks shape behavior; they don't

		determine it." - Need to critically examine assumptions - Network perceptions and how they may vary across individuals: important to understand better. - Need to take network structure and individual attributes into account simultaneously - Continue to sharpen tools for data collection - Take context into account.
16	"I don't know if network theory exists or can be developed or is meaningful ." Networks have different properties depending upon the type of network (human, biological, computer). But there are basic network mechanisms (e.g., info. transmission, social learning/imitation, uncertainty reduction)	- Consider context more deeply than we have. - Greater focus on emergent qualities - Context may drive the relevance of particular mechanisms. - Identity of nodes matters; they are not interchangeable. - Important to test our ideas with data: context specific theories may work best: "to situate the social network, you have to complement it with other parts of the envt."

17	Network theory has to be context specific (e.g., what are the nodes?). You need to figure out what type of relation you are interested in. "Networks are reductive things; you can't represent everything in a network." Context and goal of research will guide selection. Need to start with a problem.	- Context is crucial - Dynamics need further attention - More attention to different types of ties: no convincing typology of ties (facebook ties: hard to classify) - "Structural theory is concerned with theories about structure: what structures need to be; what follows from structure. But we have other theories that work in tandem that involve "partially structure and partially things outside structure (attributes of actors, etc.)"

18	"Is a grand [network] theory possible? No. But it doesn't mean that it's not a worthwhile exercise to try. Network ideas are so heterogeneous; I'm not sure grand theories are the appropriate mindset."	- The appeal of network research is the potential for connecting macro with micro - Too narrow a focus on networks; have tended to ignore other important factors (e.g., actor attributes) - More work needed on the time dimension and network dynamics - Need to take node characteristics (e.g., capacity) into account.

19	It is possible to aim at a general theory of networks even if none exists at present. How to do it? Identify menu of ideal-type structures (e.g., core-periphery); then consider causes and consequences of those structures	- Need to inject context into network theories; we have studiously ignored context. - Look at real world for identifying structural ideal patterns of interest; test theory against empirical data - Don't include everything at once: network theory is "terribly simplifying… [need to] deliberately decide which relations are worth considering [for which purpose/outcome]."
20	"Skeptical" that there can be one general theory of networks. It's contingent (on things like environmental munificence). Must consider network theories in context. Also, any general theory must be attentive to underlying mechanisms.	- Context is crucial - What causes dynamic network change: need to know more. - Need a theory that links macro and micro mechanisms - Get at coevolution of actors and networks - A general theory would have to be eclectic (would include ideas that are not traditionally considered the domain of network analysis) - Data quality is a crucial consideration - Agency must be considered
21	"I happen to think we have an extremely strong theory [of networks as" pipes" and "springs"]… Most people are unaware of it, or don't think about it at the project level… The strongest	- Networks and flow we understand well. Need to attend to networks as springs— which require that we get at the mathematics of constraints and enablers - Also need to attend to the state of

	theories in every discipline are a combination of theory plus methods and they co-develop"	nodes: node characteristics change over time: state change rarely dealt with, except in simulation work - The govt. should fund a Santa Fe-like institute for research on social networks: that's the best bet for advancement

22	"There's plenty of theory in SNA and its starting to coalesce… [not sure] how long it is going to take to get [to a unified theory] but it's definitely worth trying" Risk in taking on this project [for unified theory]: this is not the kind of task that a couple of professors and some students can pull off: it is the work of entire disciplines.	- Social networks versus other kinds of networks: distinguish human from nonhuman networks. - Context matters - Account for different kinds of ties
23	Basis of network analysis has been at hand for some time: look for relational patterns in data; make interpretations based on patterns.	- Difficult for network theory to explain cognition and motivation; but we try to explain some cognition and motivation. - Context matters: use mixed methods to more fully capture context.

24	Network theory encompasses anything and everything that involves relationships/connections. Approach to unified theory: identify families of theories from reviews of the literature. Then attempt to unify. Will be worth trying even if unsuccessful.	- More needed on network evolution - More on origins
25,26,27	Different network theories but common mechanisms	- We tend to focus on consistencies in networks; but inconsistencies (stuff that is changing) abound. - More needed on "dark side" of networks - Need to appreciate context in interpreting what networks signal in a particular setting.

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