Using Multi-theoretical Multi-level (MTML) Models to Study Adversarial Networks

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Abstract

This paper applies the multi-theoretical multi-level (MTML) model to study the creation, maintenance and dissolution of adversarial communication and knowledge networks. It begins by identifying the theoretical mechanisms that influence the dynamics and co-evolution of communication and knowledge networks in general. Next it describes how examining adversarial social networks requires an extension to the MTML framework. In particular, we describe how community ecology theory helps us better understand how the network linkages in a focal network can be influenced by other networks within the same population as well as networks within other populations in the community. Finally, we briefly describe an analytic framework that we have developed to specify (i) multi-theoretical multi-level models for the evolution of these network, (ii) agent based computational models in *Blanche* to assess the transient and long-term implications of these theoretical mechanisms on the co-evolution of the networks, and (iii) p* analytic techniques to validate these predictions using empirical data.

Some of the material in this paper has been adapted from Monge & Contractor (2003). *Theories of Communication Networks*. New York: Oxford University Press.

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Overview

To date, most network research has been limited by five major problems. First, it tends to be atheoretical, ignoring the various social theories that contain network implications. Second, it explores single levels of analysis rather than the multiple levels out of which most networks are comprised. Third, network analysis has employed limited theoretical insights from contemporary complex systems analysis and computer simulations. Fourth, it typically uses descriptive rather than inferential statistics, thus robbing it of the ability to make theoretical claims about the larger universe of networks. Finally, almost all the research is static and cross-sectional rather than dynamic. In our book, Theories *of Communication Networks* (2003), we propose solutions to all five problems. First, we have developed a multi-theoretical model that relates different social theories with different network properties. Second, the model is multi-level, offering a network decomposition that applies pertinent social theories at all network levels: individuals, dyads, triples, groups, and the entire network. Third, the model relies on a complex systems perspective, implementing *Blanche*, an agent-based network computer simulation environment, to generate and test theories and hypotheses. Fourth, the model utilizes the p^* family, a set of innovative tools for statistical network analysis, to provide a basis for valid multilevel statistical inferences. Finally, our model relates communication networks to other networks, enabling more sophisticated study of how dynamic organizational networks emerge.

This paper advances arguments in support of a multi-theoretical multi-level approach to study the emergence of adversarial networks. Recent advances in digital technologies invite consideration of organizing as a process that is accomplished by flexible, adaptive, and ad hoc networks that can be created, maintained, dissolved, and reconstituted with remarkable alacrity. We propose, and describe briefly, a Multi-theoretical Multi-level (MTML) framework -- based on network formulations of social theories -- to examine the mechanisms that influence people and organizations to forge network links with other individuals, organizations, as well as non-human agents (such as knowledge repositories). We extend the MTML framework to explicitly advance our understanding of adversarial networks.

Adversarial social networks are defined as the networks of multiple organizations within a population or the networks of multiple populations of organizations within a community (van Meter, 2001). These networks exist in the same or similar niches, competing for the same or similar resources, and seek to drive out their competitors, thus dominating the community. The relations among these nodes represent ties that vary in the extent to which they may be "adversarial." For instance, the multiple intelligence gathering organizations within the US (such as the CIA, FBI, and the NSA) are populations of organizations that are sometimes collectively referred to as the "intelligence community." The relationships between these populations range from being cooperative to competitive. Also included within the "intelligence community." are additional populations including intelligence gathering organizations of "friendly" countries as well as the intelligence gathering organizations of hostile countries and non-sovereign entities. This conceptualization of adversarial networks includes communities (or populations of organizations) within a variety of contexts including the telecommunications industry, the Wi-Fi landscape, biological warfare, the film industry, and even the development and distribution of retail consumer products. Arquilla and Ronfeldt (2001) identify several recent social movements and ideological campaigns that they identify as "netwars" in which "numerous dispersed small groups using the latest communications technologies could act conjointly across great distances" (p. 2). The groups they consider include terrorists, criminals, separatists, drug cartels, radical activists, non-government organizations (NGOs) and civil society advocates. They noted similar adversarial network patterns when they examined the organizational forms of seemingly disparate activities such as the al-Qaeda network's terrorist operations (see also Krebs, 2001), the Chechen effort to secede from Russia, the Direct Action Network's operations during the 1999 World Trade Organization summit in Seattle, Greenpeace, the International Campaign to Ban Landmines (ICBL), and the Zapatista National Liberation Army. Therefore, although the notion of adversarial networks has captured a great deal of attention in the context of terrorist networks, the theoretical scope is increasingly relevant to a much wider cast of social contexts, many of which do not carry the same illegal and illicit connotations (Bryant, Shumate, & Monge, 2002).

From "Networks in Organizations" to "Networks as Organization"

Network forms of organization are neither vertically organized hierarchies like their bureaucratic predecessors nor are they unorganized marketplaces governed by supply and demand (Powell, 1990; Williamson, 1996). Rather, network organizational forms are built on *generalized* structures that link people and knowledge in all parts of the organization to one other, while simultaneously tying them to multiple external contacts. These new forms are knowledge intensive (Badaracco, 1991), agile (Goldman, Nagel, & Preiss, 1995), and are constantly adapting as new links are added and dysfunctional ones are dropped. Thus, the evolving network form *is* the organization.

Knowledge networks by themselves and as organizational forms are understood as general concepts. Knowledge circulates throughout network organizations in a variety of forms: as individual and cognitive networks (Carley, 1995); as distributed work team networks (Hollingshead, 1998); as internal organization-wide networks enabled by Intranets (Monge & Contractor, 2001; 2003); and as external network connections via Extranets (Bar, 1995). Further, these networks are highly interdependent and co-evolve with the network forms of which they are a part. In fact, because knowledge work consists primarily of linking and integrating the various components of knowledge together, it is crucial for scholars to examine all parts of the entire knowledge network concurrently over time. This includes efforts to compile, extend, test and refine current understanding of (i) how best to characterize knowledge networks at various levels and measure their state and dynamic evolution; and (ii) the theoretical mechanisms that explain the evolution of these networks.

Multi-Theoretical Multi-level (MTML) Model for Studying the Emergence of Networks

Monge and Contractor (2003) have proposed a multi-theoretical multi-level (MTML) model to study the creation, maintenance, development, and reconstitution of network linkages in organizational and inter-organizational contexts. In general terms, we ask the question: "What are the social mechanisms that help us understand why individuals (or aggregates of individuals) seek to forge, sustain, or dissolve our network ties with other human and non-human agents?" As developments in information and communication technologies continue to reduce or eliminate the potential *logistic* barriers to our network relations, it becomes increasingly important to identify the various *social* factors that enable or constrain the development of these network linkages. Monge and Contractor (2003) identify a wide array of theories that can be used to develop network formulations. The theories and their theoretical mechanisms are summarized in Table 1. In the interest of brevity, the following summary does not include citations to the various scholars who have contributed to these theories. Details about the theories and their intellectual proponents can be found in Monge and Contractor (2003).

Theories of self-interest focus on how actors (people, organizations, etc.) make choices that favor their personal preferences and desires (Bourdieu & Wacquant, 1992; Coleman, 1986). That is, Person *i*'s decision to forge a tie with another Person *j* is motivated entirely by Person *i*'s self-interest and ability in seeking a resource that Person *j* possesses. Two primary theories in this area are the theory of social capital (Burt, 1992, 2001; Lin 2001) and transaction cost economics (Williamson, 1975, 1985). Distinct from human capital, which describes individual personal characteristics, social capital focuses on the properties of the communication networks in which people are embedded. Structural holes in the network provide people opportunities to invest their information, communication, and other social resources in the expectation of reaping profits. Transaction cost economics examines the information and communication costs involved in market and organizational transactions as well as ways in which to minimize these costs. Network forms of organization provide an alternative to markets and hierarchy, which focuses on embeddedness in complex networks (Powell, 1990). Information flows are essential in determining to whom a firm should link and joint value maximization offers an alternative principle to minimizing transaction costs (Zajac & Olsen, 1993). Self-interest mechanisms are likely to foster the formation of separate adversarial networks. These theories suggest that each network will invest its own social capital to expand its own network. They also suggest that each network will seek to exploit the structural holes of its adversaries.

Theories of mutual interest and collective action examine how coordinated activity produces outcomes unattainable by individual action (Marwell & Oliver, 1993).

That is, Individual *i*'s and Individual *j*'s decision to forge a tie is motivated by their belief that it serves their mutual (or collective) interest in accomplishing common or complementary goals. One theory that exemplifies this perspective is public goods theory (Hardin, 1982; Samuelson, 1954), which examines the communication strategies that enable organizers to induce members of a collective to contribute their resources to the

Table 1. Selected Social Theories and their Theoretical Mechanisms

Theory	Theoretical Mechanism
Theories of Self-Interest	
Social Capital	Investments in opportunities
Structural Holes	Control of information flow
Transaction Costs	Cost minimization
Mutual Self Interest & Collective Action	Joint value maximization
Public Good Theory	Inducements to contribute
Critical Mass Theory	Number of people with resources & interests
Cognitive Theories	Cognitive mechanisms leading to:
Semantic/knowledge Networks	Shared interpretations
Cognitive social structures	Similarity in perceptual structures
Cognitive Consistency	
Balance theory	Drive to avoid imbalance & restore balance
Cognitive Dissonance	Drive to reduce dissonance
Contagion Theories	Exposure to contact leading to:
Social Information Processing	Social influence
Social Learning Theory	Imitation, modeling
Institutional Theory	Mimetic behavior
Structural Theory of Action	Similar positions in structure and roles
Exchange and Dependency	Exchange of valued resources
Social Exchange Theory	Equality of exchange
Resource Dependency	Inequality of exchange
Network Exchange	Complex calculi for balance
Homophily & Proximity	Choices based on similarity
Social Comparison Theory	Choose comparable others
Social Identity	Choose based on own group identity
Physical proximity	Influence of distance
Electronic Proximity	Influence of accessibility

Theories of Network Co-evolution	Variation, Selection, Retention
Organizational ecology	Competition for scare resources
NK(C)	Network density and complexity
Community ecology	Commensalist/Symbiotic relns b/w populations

realization of a public good. Mutual interest often conflicts with the individual self-interests of the members of a collective and sometimes leads to free riding (Olson, 1965) and other social and communication dilemmas (Bonacich & Schneider, 1992; Kalman, Monge, Fulk, & Heino, 2002). Network relations are often essential to the provision and maintenance of the good. Mutual interest theories apply largely to the separate adversaries, as they seek to foster their own agendas in consort with those of like minds. Insight can be gained by analyzing what the various networks define as their collective goods and bads, and the strategies and enticements they use to induce others in join their networks or at least support their separate causes.

Contagion theories address questions pertaining to the spread of ideas, messages, attitudes, and beliefs through some form of direct contact (Carley, 1991; Contractor & Eisenberg, 1990). For instance, Person *i*'s decision to forge a tie with another Person *j* is motivated by others in Person *i*'s network who have forged ties with Person *j*. Contagion theories are based on a disease metaphor, where exposure to communication messages leads to "contamination." Inoculation theory (McGuire, 1966) provides strategies that can be used to prevent contamination. Two competing contagion mechanisms have received considerable attention in the research literature. Contagion by cohesion implies that people are influenced by direct contact with others in their communication networks (Erickson, 1988). Contagion by structural equivalence suggests that those who have similar structural patterns of relationships within the network are more likely to influence one another (Burt, 1987). Social information processing (social influence) theory (Fulk, Schmitz, & Steinfield, 1990) suggests that the attitudes and beliefs of people become similar to those of the others in their communication networks. Social cognitive theory (Bandura, 1986) and institutional theory (DiMaggio & Powell, 1983; Meyer & Rowan, 1977) posit that mimetic processes lead to contagion, whereby people and institutions imitate the practices of those in their relevant networks. Contagion theories apply to adversarial networks in at least three ways. First, each contending network attempts to extend itself by acquiring and linking new members that accept its core identity. Second, they seek to infect the members of their adversaries' networks with messages, information, and ideologies that will undermine or destroy them. Finally, the adversaries seek to defend themselves by inoculating the members of their own networks against their rivals' efforts to infect them.

Cognitive theories explore the role that meaning, knowledge, and perceptions play in communication networks. Individual *i*'s decision to forge a tie with another Person *j* is motivated by who Individual *i* thinks Person *j* knows or what *i* thinks *j* knows or possesses. *Semantic networks* are created on the basis of shared message content and similarity in interpretation and understanding (Carley, 1986; Monge & Eisenberg, 1987). A complementary perspective views interorganizational networks as *structures of* *knowledge* (Kogut, Shan, & Walker, 1993). Creating interorganizational alliances requires building extensive knowledge networks among prospective partners and maintaining them among current partners. These knowledge networks are the mechanisms though which organizations share both explicit and tacit knowledge. *Cognitive communication structures* represent the perceptions that people have about their communication networks, that is, about who in their networks talk to whom (Corman & Scott, 1994). These individual cognitive communication networks can be aggregated to provide a collective or consensual view of the entire network (Krackhardt, 1987). Cognitive consistency theory examines the extent to which the attitudes, beliefs, opinions and values of network members are governed by a drive toward consistency or balance (Heider, 1958). The theory suggests that network members tend toward cognitive similarity as a function of the cognitive balance in their networks rather than alternative mechanisms such as contagion (Davis & Leinhardt, 1972; Holland & Leinhardt, 1975). *Transactive memory systems* consist of knowledge networks in which people assume responsibility for mastery among various aspects of a larger knowledge domain. In this way the collective is more knowledgeable than any component (Hollingshead, 2000, Moreland, 1999; Wegner, 1987). Knowledge repositories linked to the larger knowledge network facilitate knowledge storage and processing (Wegner, 1995). While knowledge flow is essential to an effective knowledge network, communication dilemmas sometimes lead people to withhold potentially useful information (Kalman, et al., 2002). These theories offer insights into adversarial networks. Competitors often develop differing semantic networks based on ingroup-outgroup polarization. While developing their own knowledge networks, competitors seek to undermine the knowledge networks of others, often by disseminating misinformation and faulty knowledge to their opponents, including their cognitive communication structures. Finally transactive memory systems help identify where crucial expertise lies within knowledge networks, thus helping adversaries to build their own expertise and to mount attacks their opponents.

Exchange and dependency theories seek to explain the emergence of communication networks on the basis of the distribution of information and material resources across the members of a network (Emerson, 1962, 1972a, 1972b; Homans, 1950). That is, Person *i*'s decision to forge a tie with another Person *j* is motivated by *i*'s interest in seeking a resource that *j* possesses, and in exchange offering Individual *j* some resource that *i* possesses and is of interest to *j*. People seek what they need from others while giving what others also seek. The exchange form of this family of theories is based largely on equality, assuming that giving and getting generally balances out across the network (Bienenstock & Bonacich, 1992; Cook, 1982). The dependency form emphasizes inequality and focuses on how those who are resource rich in the network tend to dominate those who are resource poor (Benson, 1975; Freeman, 1977, 1979). Consequently, power, control, trust, and ethical behavior are central issues to both theories (Oliver, 1991). Adversaries seek to dominate each other, perhaps to the point of destroying all opponents. While they are likely to utilize exchange mechanisms within their own networks, adversarial networks are dominated by attempts to assert dependency relations on their competitors.

Homophily and proximity theories account for network emergence on the basis of the similarity of network members' traits (Brass, 1995) as well as their similarity of place (Homans, 1950). Agent *i*'s decision to forge a tie with another Agent *j* is motivated by *i* and *j* sharing common traits (gender, tenure, etc.) or being proximate in physical or electronic spaces. Traits represent a variety of personal and demographic characteristics such as age, gender, race, professional interests, etc. (Carley, 1991; Coleman, 1957, Marsden, 1988) Social comparison theory suggests that people feel discomfort when they compare themselves to others who are different because they have a natural desire to affiliate with those who are like themselves (Festinger, 1954). Of course, this ignores the old adage that opposites attract, which would argue for a heterophily mechanism. Proximity theories argue that people communicate most frequently with those to whom they are physically closest (Monge, et al, 1985). The theory of electronic propinquity extends this to the realm of email, telephones and other forms of electronic communication (Contractor & Bishop, 2000;Korzenny & Bauer, 1981; Wellman, 2001). Homophily theory suggests that networks engaged in adversarial relations are likely to be comprised of people and organizations who are more similar to each other than to the members of their competitors' networks. A block model of all adversarial networks (in a given adversarial community) combined into a supra-network would reveal greater similarity within than between blocks. Proximity theory indicates that competing adversarial networks should exist in separate physical and electronic spaces. Yet similarity of traits and space also predicts likely points of contact between competitors and possible locations for penetration of one network by another, both overt and covert.

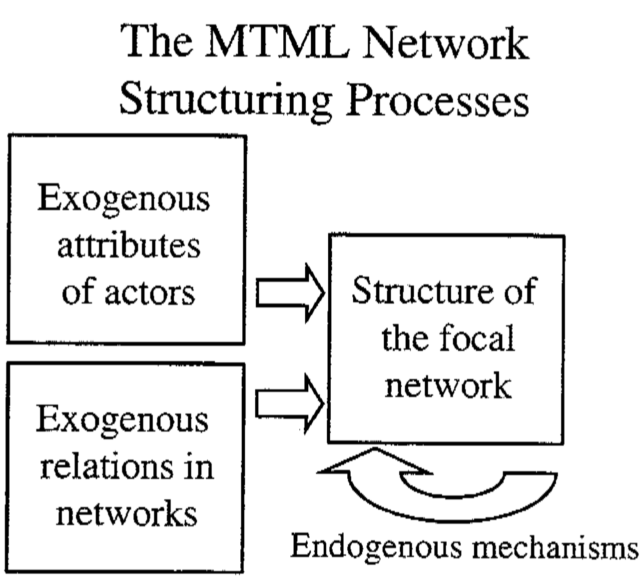
Coevolutionary theory extends traditional evolutionary theory that posits aspirations towards "fitness" based on mechanisms of variation, selection, retention, and struggle or competition (Aldrich, 1999; Campbell, 1965; Hawley, 1986). For example, Entity *i*'s decision to forge a tie with Entity *j* is motivated entirely by *i*'s belief that the network linkage will increase *i*'s fitness (measured as performance, survivability, adaptability, robustness, etc.; Hannan & Freeman, 1977). Random or planned variations in organizational traits occur, which are selected and retained on the basis of their contribution to organizational fitness and survival(Baum, 1996; Nelson & Winter, 1982). Coevolutionary theory articulates how communities of organizational populations linked by intra-and-interpopulation networks compete and cooperate with each other for scare resources (Astley, 1985; Kauffman, 1993). In order to survive, organizational networks must adapt to the constantly changing environmental niches in which they find themselves while also attempting to influence the ways in which their environments change (McKelvey, 1997).

In most social contexts, more than one of the theoretical mechanisms reviewed above simultaneously influence people. In some cases different theories, some using similar theoretical mechanisms, offer similar explanations but at different levels of analysis. For instance, contagion mechanisms help explain the emergence of networks among individuals as well as among adversarial organizations. In other cases, different theories offer contradictory explanations for the emergence of networks. For instance, theories of self-interest would suggest that adversarial networks create links with others who are indirectly connected to their adversaries, thereby increasing the amount of nonredundant information that can be gleaned. On the other hand, cognitive theories of balance suggest that people seek to be friends with enemies of their enemies thereby increasing their cognitive need for balance.

EXTENSIONS TO MTML MODEL FOR THE STUDY OF ADVERSARIAL NETWORKS: A COMMUNITY ECOLOGY PERSPECTIVE

The MTML model proposed by Monge and Contractor (2003) focused largely on the social mechanisms that explain the creation, maintenance, and dissolution of network linkages within *single* networks. It does so by examining the structural tendencies of various relations (such as communication linkages, knowledge linkages, trust relations) among the actors within that network and the attributes (such as gender, level in the hierarchy, and level of expertise) of the actors within that *same* network. Also included in that model, though not extensive explored, was the influence of other networks on the focal network as well as the influence of the focal network at previous points in time. These relations are summarized in Figure 1. In the case of adversarial networks it is

Figure 1. The MTML network structuring process



important to further explore the ways in which competitors influence each other and coevolve within the community.

There are several examples of how adversarial networks influence the structuring of ties within a focal network. For instance, Baker and Faulkner (1993) note that the activation of ties within a covert network are often constrained by the structure and scope of ties within the adversaries' networks. The desire to communicate, share information, and coordinate within a covert network have to be reconciled with the desire to shield the identity, structure and content of the focal network --- that is, the very survival of the covert network. Indeed as Weiser (2001) says a recently uncovered terrorist manual notes explicitly the premium put on secrecy over communication. Further, as Rothenberg (2001, p. 41) states, the viability of terrorist networks is specifically enhanced by other networks in the community – "the American democratic system that they seek to destroy, a system that permits open movement, freedom of choice, and respects privacy." As described earlier, many of the MTML mechanisms (such as self-interest, social exchange, and proximity) can account for how competing networks configure themselves to advance their position in the community while decreasing the viability of their competitors.

Community ecology theory (Aldrich, 1999; Baum & Singh, 1994; Hawley, 1950) provides a framework to explain the coevolution of populations of adversarial networks within a community. Community ecology examines multiple populations of differing organizations as well as the various niches in which they occur. Organizations must typically compete with others in their own populations to acquire the resources they need to survive in their selected environments. For example, Barnett (1990) studied the competition among the members of the population of the telephone companies in Pennsylvania from 1879-1934, until one company AT&T dominated the market. And Staber (1989) studied the emergence or worker and consumer coops showing how they competed for customer loyalty. Likewise members of the population of US intelligence organizations (such as the FBI, CIA, NSA) compete with each other for resources, jurisdiction, and legitimacy. But internal competition is not the only challenge that populations face. They must deal with the members of other populations of friendly and adversarial intelligence organizations outside the US as well as of non-governmental organizations that coexist in their niche. For example, Haveman (1992) studied the competition between banks and savings and loan associations for customers and their funds under changing regulatory conditions. And Carroll and Swaminathan (1992) examined the emergence of microbreweries and brewpubs who competed with the mass producers. Often organizations must compete, but under some conditions organizations from different populations can also *cooperate*, seeking mutually beneficial outcomes, a fact that Kauffman (1995, p. 215) says is much more commonly recognized now than in earlier theorizing. Aldrich (1999, citing Hawley, 1950) argues that two types of interdependence drive community dynamics: commensalism and symbiosis. "*Commensalism* refers to competition and cooperation between similar units, whereas *symbiosis* refers to mutual interdependence between dissimilar units" (p. 298, italics in the original). Thus, in large part, relations both within and among populations govern communities. The first relation is the degree to which similar populations in the same niches compete or cooperate and the second is the degree to which different populations in the same or different niches support each other.

An important issue that has arisen with regard to community ecology is how to define a community (Aldrich, 1999; DiMaggio, 1994). Hawley's (1950) original sociological work on community ecology focuses relationships within geographically and temporally bound communities. As community ecology has been refitted for organizational scholarship, the definitions of community have taken a more functional approach (Ruef, 2000). That is not to say, however, that organizational scholars completely agree on how community should be defined, operationalized, or analyzed. Astley's (1985) organizational model of community focuses on the technology-based interrelationships between populations. Barnett and his colleagues (Barnett, 1994; Barnett & Carroll, 1987; Barnett, Mischke, & Ocasio, 2000) define community on the basis of commensalist and symbiotic relationships between organizations. Hannan and Carroll (1995) broaden the scope of this definition, asserting that community "refers to the broader set of organizational populations whose interactions have a systemic character, often caused by functional differentiation" (p. 30). Rosenkopf and Tushman (1994) add that context is important, in their case the technological context. Aldrich (1999) and Ruef (2000) add that the populations in a community should be organized around a "core," whether it be technological, normative, functional, or legal-regulatory. Ruef (2000) goes about organizing his community of health care populations by focuses on four main functions of the health care field. Aldrich (1999, p. 301) proffers this succinct definition: "An organizational community is a set of coevolving organizational populations joined by ties of commensalism and symbiosis through their orientation to a common technology, normative order, or legal-regulatory regime." (p. 301).

Aldrich (1999, p. 302) proposes a taxonomy of eight possible relations between organizational populations based on the effects these relations have on each of the population. Aldrich proposes 6 types of commensalist relations (those that occur among similar units): full competition (where each population negatively impacts the other); partial competition (where only one of the populations has a negative effect on the other); predatory competition (where one population has a positive effect on the other while the latter has a negative impact on the former); neutrality (where neither population has a positive or negative impact on the other); partial mutualism (where one has a positive effect on the other, but the latter has no impact on the former), full mutualism (where both have positive impacts on each other). While full mutualism is defined as a commensalist relation (between similar populations), symbiosis is defined as a mutually beneficial relation between dissimilar populations. Finally, Aldrich (1999; p. 302) defines a dominance relation where a "dominant population controls the flow of resources to other populations (Hawley, 1950). The structure of the community and the coevolution of the populations of networks that comprise it depend on the outcome of commensalistic and symbiotic relations."

Aldrich's (1999) review illustrates several research examples for each of these intra- and inter-population relationships. However, most of the extant research in this area has examined only two populations at a time. Clearly, the community ecology theory posits an examination of multiple (not just two) populations within the community and their co-evolving influences on one another. Social network analysis in general, and the MTML framework proposed here, is particularly well-suited to this task. For instance, we can begin to hypothesize and empirically test how the populations within the community co-evolve when relations *among* the competing populations are considered at the triadic, sub-groups, and global levels. To what extent is the creation of ties within adversarial networks influenced by their common technology, normative order, or legal-regulatory regime? And, to what extent are the creation, maintenance, and dissolution of network relations within focal adversarial networks influenced by the various commensalist relations (within other organizations in the same population) and symbiotic relations with other populations within the community? Thus community ecology theory provides an important addition to the previously described MTML mechanisms in explaining the emergence of adversarial networks.

ANALYTIC FRAMEWORK FOR STUDYING MTML MODELS

The previous section has described theoretical mechanisms that offer explanations for the co-evolution of communication and knowledge networks. The schematic in the following figure describes a comprehensive analytic methodology developed by Contractor et al (1999) as part of our ongoing NSF-funded research to computationally model, empirically assess, and statistically validate the multiple theories that explain co-evolution of knowledge networks. These include changes resulting from the interventions of technologies. The schematic shows the relationship among the key elements of the analytic framework approach: (1) theory building/hypothesis formulation about mechanisms of network co-evolution; (2) computational modeling/simulation of those mechanisms and how they produce emergent behavior; (3) collection and analysis of empirical data, and (4) development and deployment of novel "community-ware" knowledge network enabling tools. The new kinds of data analysis and theory validation are enabled by (5) advances in p* statistical techniques for modeling and analyzing network data.

Table 2 provides an illustration of how p* network analytic techniques can be used to simultaneously test multiple theories at multiple levels (Contractor, Wasserman, & Faust, 2002). Table 2 summarizes various genres of network hypotheses in terms of the probabilities of graph realizations exhibiting the hypothesized relational property. In each case, the hypothesis is that graph realizations with the hypothesized property have larger probabilities of being observed. In other words, the probability of ties being present or absent in the graph reflects the hypothesized relational property. The table begins by distinguishing endogenous and exogenous variables that influence the probability of ties being present or absent in the focal network. It should be noted that the exogenous-endogenous distinction being made here is not equivalent to similar terminology used in the development of causal models in general and structural equation models in particular. Unlike its use in causal modeling, endogenous variables here are not predicted by exogenous variables. Here, both explain structural tendencies of the network.

Endogenous variables (Rows 1 through 4 in Table 2) refer to various relational properties of the focal network itself that influence the probability of ties being present or absent in the same network. From a meta-theoretical perspective, these endogenous variables capture the extent to which relational properties of the network influence its self-organization. *Exogenous variables* (Rows 5 through 11 in Table 2) refer to various properties outside the specific relation within the focal network that influence the probability of ties being present or absent in the focal network. Hence exogenous variables include the attributes of the actors in the network, additional network relations among the actors, the same network relation at previous points in time, as well as other networks within the same population or other populations. Within each of these two categories (i.e., endogenous and exogenous variables), the table offers a further sub-classification based on the extent to which the probability of ties being present or absent in the network are influenced by properties at the actor, dyad, triad, and global levels. In addition to including genres of network hypotheses, the third column in Table 2 also

Figure 2. Analytic framework to study the coevolution of adversarial networks

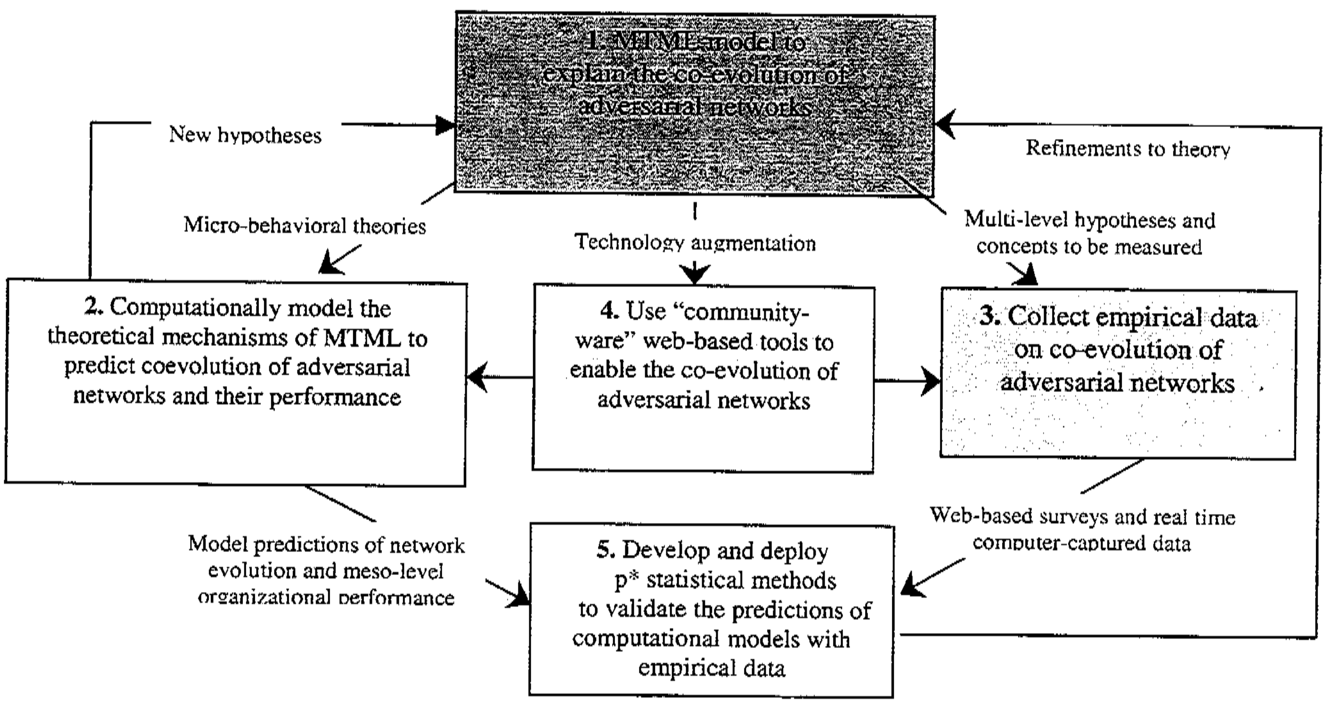


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Table 2. Summary of a multilevel multi-theoretical framework to test hypotheses about adversarial networks (Variable of interest: Probability of the realizations of a graph)

Independent variable	**Examples of specific measures**	**Hypotheses:** Graph realizations where there is greater likelihood of …
1. Endogenous (same network): *Actor level*	Actor centrality, structural autonomy.	… high actor centrality have higher probabilities of occurring *(e.g., Theory of structural holes)*
2. Endogenous (same network): *Dyad level*	Mutuality, Reciprocation	… high mutuality have higher probabilities of occurring *(e.g., Exchange Theory)*
3. Endogenous (same network): *Triad level*	Transitivity, cyclicality	… high cyclicality have higher probabilities of occurring *(e.g., Balance Theory)*
4. Endogenous (same network): *Global level*	Network density, centralization	… high centralization have higher probabilities of occurring. *(e.g., Collective action theory)*
5. Exogenous: Actor attributes (*Actor level*)	Age, gender, organization type, education	… ties between actors with similar attributes have higher probabilities of occurring *(e.g., Theories of homophily)*
6. Exogenous: Actor attributes (*Dyad level*)	Differential mutuality and reciprocation	… mutual ties between actors with similar attributes have higher probabilities of occurring *(e.g., Exchange Theory)*
7. Exogenous: Actor attributes (*Triad level*)	Differential transitivity and cyclicality	… transitive (or cyclical) ties between actors with similar attributes have higher probabilities of occurring. *(e.g., Balance Theory)*
8. Exogenous: Actor attributes (*Global level*)	Differential network density, centralization	… network centralization among actors with similar attributes have higher probabilities of occurring. *(e.g., Collective action theory)*
9. Exogenous: Network *(Other relations)*	Advice, friendship network	… communication ties co-occurring with ties on a second relation have higher probabilities of occurring. *(e.g., Cognitive theories)*
10. Exogenous: Network *(Same relation at previous point in time)*	Communication network	… ties between actors co-occurring with ties at preceding points in time have higher probability of occurring. *(e.g., Evolutionary theories)*
11. Exogenous: Other networks (*Within the same population and in other populations*)	Actor, dyad, triad, and global metrics in other networks	… ties between actors co-occurring due to structural properties of other networks within the same population and other populations within the community (e.g., *Community Ecology theory*)

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