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NETWORK ANALYSIS AND SOCIAL DYNAMICS

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Network analysis, an area of mathematical anthropology and sociology crucial to the linking of theory and observation, developed dramatically in recent decades. This made possible a new understanding of social dynamics as a synthesis of network theories. Concrete links can be identified between the actions of self-reflective agents, with rich information processing and decision processes deeply embedded in social worlds, and emergence or change in the self-restructuring systems they operate—including the emergence of organizations, groups, institutions, norms, and cultures.

The past four decades saw a massive development of concepts and tools for network analysis, initially spurred by the anthropologist Clyde Mitchell (1969) and the sociologist Harrison White (1992). These developments enabled burgeoning applications to ever-wider sets of problems in the social sciences. The trajectories of social network analysis in the two disciplines, however, have been very different. Network approaches in sociology became rather quickly a central theoretical paradigm for integrating the dynamics of human agency with theories of the feedback between structural constraints and the emergence of institutions out of human interaction (Mullins 1973; Berkowitz 1982; Burt 1982; Wellman 2000). Still, even in sociology, the development of methodology (Wasserman and Faust 1994) far outstripped that of an integrated theory of networks that situates explanatory principles in a common conceptual

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framework. The anthropology of the 1960s failed to see the more general relevance of an array of network modeling possibilities to social theory[1] and relegated network analysis to a "toolkit" for specialized problems collateral to, but mostly outside of, institutional and cultural analysis.

In the past decade, however, the effort that anthropologists have put into long-term field sites has begun to pay off in terms of longitudinal network studies of the dynamics of social networks (see Johansên and White 2002). The rich ethnographic context that long-term field site data bring to network analysis has begun to contribute in major ways to foundational theory in the social sciences. Studies in this context have begun to integrate, in an emergent network theory, "models of how complex, information processing, self-reflective, self-restructuring systems operate, develop and change" (Read 1990). Network theory has helped to formulate both general explanatory frameworks for explicating how multiple types of phenomena are linked and feedback on one another through their embeddings in multiple overlapping and interpenetrating network configurations. Rich ethnographic groundings for the study of multiple embedded network processes have begun to provide breakthroughs in the study of feedback processes (White and Houseman 2003). I will focus here on applications used to date for several long-term, field site analyses.[2]

CONCEPTUAL PERSPECTIVE

One of the key ingredients of scientific explanation and the testing of theory is the development of models that relate first principles, as a function of measurable parameters of interaction and structure, to a diversity of observable outcomes. Network theory generally, in so doing, attempts to explicate how social and cultural phenomena emerge out of interaction. (Such outcomes are path dependent.) This may be done by

[1]Interest in networks largely died out in anthropology by the mid-1970s once those who had begun experimenting with the approach in the 1960s turned away from problems of fluid social structure to the study of transactions, ritual enactment, symbolic action, and contemporary themes of cultural anthropology. Anthropologists with a cognitive focus narrowed their studies to the shared components of egocentric cognitive constructions in relation to observed behavior. These studies unfortunately did not capture the interests of the field at large.

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measuring the properties of local interactions as well as different kinds of emergent structure, ideally through time, across observable networks of communication and of social and instrumental relations, events, and activities. Table 1 shows some of the network concepts applicable to domains of social theory. Coupled with the modeling of fundamental interaction processes, they are designed to allow for measuring local network properties and structural emergents in order to test hypotheses about processes, interactions, and outcomes.

The middle column in Table 1 lists the typical kind of mathematical model used for a particular concept. These different models can be used in combination both to build a general framework of interrelated models useful for formulating network theory and to help test some of the hypotheses derived from network theory.

STRUCTURE AND DYNAMICS

Structure

Table 1 is organized in terms of structural properties of networks. Topic A, solidarity, deals with relations within groups, including aspects that are both relational and ideational—networks of behaviors as the relational component of solidarity or of attitudes as the ideational component. Group cohesion, for example, may emerge from a certain density of random encounters (Erdös and Rényi 1960), with the measurement and boundedness of the emergent groups defined by maximal sets of members (k components) that are robust to disconnection by removal of subsets of fewer than k members (Moody and White 2003). Graphs evolving through the random addition of edges develop hierarchically nested k components as a function of the density of edges, and inequalities in the number of edges incident to each node follow an exponential distribution correlated to the height of cohesion in the largest of the nested stack of k components of which each node is a member (see Dynamics section).[3] Menger's (1927) theorem is that all pairs of members of a k component also have k or more node-distinct paths between them. Hence, considerable structure may develop out of interactions that are random, which usually occur only within some locally bounded context. As for the sharing of cultural elements that develop out of interaction in a locally

[3]If nodes are also added randomly there is an early starter advantage and the distribution changes to power law.

Table 1. Network concepts in the literature streams of social theory

Concepts and some numbered principles	Network aspects	Measures of network structure	Methods authors	Classic works: Authors or principles
A Solidarity	Intragroup	**Pattern 1**		Durkheim
Group (1)	**Cohesion**	*k*-connectedness	Harary and White	Lewin
Random encounters	**Opportunity**	Exponential distributions	Erdös and Reyni	Blau
Culture	**Consensus**	One-dimensional covariance	Romney and Batchelder	Tylor
Moral economy	**Affect and division**	k-balance	Harary, Davis	Heider
B Social Worlds	Intergroup	**Patterns 2 and 3**	Harary and Batell	Multilevel
Quasi-random Encounters	**Biased mixing**	Power law distributions	De Solla Price	Early and Rich-get-richer
Small world (3)	**Reach- and searchability**	Clustering & low average distance	Watts and Strogatz; Kleinberg	Milgram
Economy (2) and Amoral economy	**Exchange; conflict**	Graph homomorphism	Harary, Coser	Weber, Simmel, Gluckman
Law and social control	**Mediation**	Conditional homomorphism	Harary	Simmel, Lévi-Strauss, Nadel
C Specialization	Activity	**Patterns 4 and 5**		
Position (4)	**Structural equivalence**	Structural homomorphism	H. White	Homans
Analogy (4)	**Regular equivalence**	Regular homomorphism; overlap lattice	D. White and Reitz Ganter and Wille (1999)	Merton, Goodenough
Specialized allocation (5)	**Division of labor**	Task allocation homomorphism	Oeser and Harary	Durkheim
D Inequality	Ordination	**Pattern 6**		
Distributional	**Preferential attachment**	Power law	de Solla Price Freeman	Pareto Rich-get-richer
Centrality (6)	**Influence**	Betweenness	Barabási	Bavelas
Supervisory authority	**Power**	Triadic interlock	J. Davis, D. White	Nadel
Hierarchy	**Authority**	Levels measure	Reitz (1982)	Lewin
E Resilience (7)	Redistributed transformation	**Pattern 7**		

bounded context, to the extent that interactions are random or these elements are learned independently from a common source, there emerges a group "consensus" that is recoverable (e.g., reconstructing the shared source) from one-dimensional covariance in the pattern of sharing across dyads in the network. This is the basis for Romney et al.'s (1986) consensus theory for the study of culture. Cohesive groups with cultural consensus, however, may also divide and differentiate. One source of internal division is a moral economy in which clusters form out of mutually positive ties but also differentiate due to negative linkages between clusters. Small local differences in initial phases of differentiation may provide self-amplifying seeds for what later become global differentiations (see Dynamics section).

Social worlds, topic B in Table 1, deal with the structure of networks viewed in the large, where links between individuals are not bound by a local context but may cross the boundaries of diverse and often cross-cutting groups or social categories, as in Blau's (1977, 1994) theory of intersecting social circles. A (large) network that is small world (SW) has clusters of densely connected nodes. In addition, like a random network, an SW has relatively small average distance between nodes. The *degree* of a node is the number of edges that connect it directly to other nodes. For an Erdös–Rényi (ER) random graph with n nodes, in which edges occur with uniform probability, the average distance between nodes is of the order $\ln n/\ln d$, where d is the average degree. For many SW networks, high-degree nodes attract proportionally higher numbers of edges so that the histogram of degree follows a power law distribution (de Solla Price 1965, 1980; Barabási 2002) with number N_d of nodes having degree d proportional to $1/d^{\beta}$. Power law degree distributions create network hubs, and dense cores of hubs, that drastically reduce average distance.[4] To be effective, SWs also require searchability, defined by Kleinberg (2000) as the ability to navigate from one node to another in search of a target using only locally available information about which of the next

[4]Power law graphs with exponents in the range $\beta > 3$ also have, like ER graphs, average distance between nodes on the order of $\log n/\log d$. Many "Internet, social and citation networks are power law graphs with exponents in the range $2 < \beta < 3$," and like "a power-law random graph with exponent between 2 and 3," have an octopus-like structure for a giant component with "diameter of order log n" and "a dense subgraph, that we call the core, having $n^{c\hat{}\log\log n}$ vertices," average distance within the core of order $\log\log n$, and each node in the core is within a distance of order $\log\log n$ with a core vertex of degree at least $O(\log n)$ (Chung and Lu 2002).

links is in some way closer to it (consistent with the pre-1969 Travers and Milgram SW experiment) and to locate the target in polynomial time. Exchange economies (with positive-tie networks) and conflicts (with negative-tie networks) are usually SW networks that are in this sense navigable but that also display characteristic role structures—that is, differentiation of positions in the network that serve social or economic objectives, including that of mediation. Much of the role structure of a network can be discovered empirically by investigating mappings of actors and relations that reduce the actors or relations (or both) into a much smaller number of sets for which the mapping of relations are homomorphic in preserving salient aspects of the structure of the original network (Lorrain 1974; Lorrain and White 1971; White and Reitz 1983).[5] *Graph-equivalent* positions in a network are sets of nodes having no edges between them, as in the coloring of countries on a planar map or globe. *Regular-equivalent* positions are sets of nodes that have either the same nonempty relation to other nodes or each to equivalent nodes. *Structural-equivalent* positions are sets in which equivalent nodes have the same relations, empty or not, to every other node. Reitz and White (1989) show how these equivalences correspond to differences among relation-preserving homomorphisms.

Specialization, topic C in Table 1, also deals with equivalence of position in networks. Structural equivalence, exemplified by positions in production markets (in which producers of the same goods can sell to the same buyers and consumers of the same goods can buy from the same producers), place equivalent actors in direct competition. In the case of production markets (White 2002, 2003), this induces differentiation of market profiles by quality and price. Regular equivalence allows the possibility of analogous linkages with indirect competition, which may show even stronger constraints, as in the case of the world economy

[5]While the stacked k components of relational cohesion may have overlapping and hierarchically nested sets of nodes, network homomorphisms produce sets of nonoverlapping nodes. Graph homomorphisms are the special case of network homomorphisms in which there are no loops (edges connecting a node to itself) in the network and no loops in the homomorphic mapping of the network. A graph homomorphism also corresponds to a coloring of nodes such that no pairs of nodes of the same color are connected, so that relations are considered "external" to the sets that are grouped together, just as a change in coloring on a planar map or globe denotes a border demarcating neighboring countries. While relational cohesion deals with relations *internal* to k components, exchange and conflict deal with relations that are *external* to nodes that occupy.

(Smith and White 1992). Division of labor arises out of differentiation of positions in economic or conflict networks and rising velocities of exchange or aggression. Modeling of this type of differentiation requires analysis of the three-mode network consisting of people by positions they occupy by tasks performed (Oeser and Harary 1964, 1979).

Inequality, topic D in Table 1, can be measured in network data from differences in degree (preferential attachment), potential for mediation or betweenness (Freeman 1979), or in other aspects of centrality. Some kinds of networks have partial orderings in such relations as direct authority or indirect power over other dyads in the form of supervisory authority (Nadel 1957).

Resilience, topic E in Table 1, contrasts with robustness, in which a pattern of flows that sustains access to valued resources survives under changing conditions in the broader environment. Resilience is a reconfiguration or transformation that redistributes and rebundles such network flows, under changing conditions, to maintain or intensify valued and sustainable outputs.

Dynamics

Several types of discontinuous qualitative change or "tipping points" in network structure occur with gradual change in network interaction. These include the following:

Transitions to connectedness that allows percolation or diffusive spread throughout a network[6] to local clustering that fosters heterogeneity, and to giant *k*-component cores of connected networks that foster hierarchically organized levels of cohesion.

Convective alignment or coherent streaming of network flows,[7] including circular flows, channeled, or coherently directed flows.

Propagation, or omnidirectional broadcast, as in mass media effects on network changes with respect to omnidirectionally distributed nodes.

[6]Diffusive processes follow a pattern of movement analogous to Brownian motion, in which distance traveled along a random path varies with the square root of time. This might apply to gossip, for example, or spread of an infectious disease.

[7]A convective process follows a pattern of movement in which distance traveled in a straight line or along a single channel varies with time. Navigation to a target illustrates this kind of process.

Another source of dynamical instability occurs in the variable ways that the coarser formal patterns of grouping (topic A, item 1) and group exchange (topic B, item 2) interact with the logics of analogy and allocation (topic C, items 4 and 5) used to superimpose reorderings on networks. Items from topics numbered in the leftmost column of Table 1 are at the center of Figure 1. The figure summarizes heuristic hypotheses discussed in the next section and puts them in a dynamical context. The arrows denoting dynamical mappings among these formal structural patterns (as labeled in the inner circled elements of the figure) represent continual adjustments between network grouping principles (cohesion, exchange, and conflict: items 1 and 2) to the left and superimposed logics of equivalence and allocation (position, analogy, and specialization: items 4 and 5) to the right. The handles joining items 1 and 2 and 4 and 5 and the label "3 SW" on the left- and right-hand sides of the inner part of the figures are intended to indicate that these are multilevel navigable small-world networks with raw behavior linking individuals on the left and superimposed organizational groupings (often homomorphic) on the right.

Figure 1 attempts to show that the grouping principles tend to organize and closely interlock activity with cognition, both of which are subject to tight constraints as to how activities and the catalytic symbols

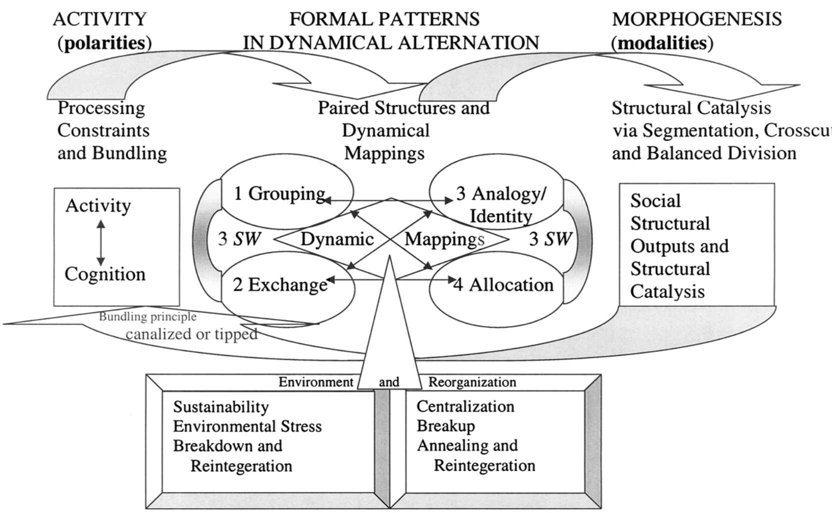

Figure 1. Process model of relational coherence between statics and dynamics.

used in organizing activities must be cohesively bundled (and actors bundled into groups) to meet the energy budgets of group members and requirements for common-code coordination among them.[8] Activity bundling and its cognitive representations, however, are continually acted upon by larger environmental/demographic changes (as shown by the labeled panels at the bottom of the figure) that operate to reorganize and renormalize existing patterns into new action-directive logics that utilize analogy, identity, and allocation. This renormalization operates on the basis of deontic logics of rights and obligations attendant upon status, with the dynamics of emergent role structures governed by principles of morphogenesis following deontic modalities (shoulds and oughts). The keys to these processes reside in how perceived structural patterns are mobilized symbolically to catalyze new demands for deontological bundling and how the social processes of segmentation, cross-cutting memberships, and balancing, via mechanisms consistency or insulation, play into social, moral, political, and quasi-legal coalitions supporting collaborating or competing deontologics as visions of possible future trajectories.

POTENTIALS FOR INTEGRATION OF THEORY AND MEASUREMENT

Dynamical Evolution of Coherence among Formal Patterns

The goal of putting diverse ideas from networks and dynamics together into a single framework is to develop process models of relational coherence. How do elements assort and then cohere and synchronize in a (complex) social system? "Structural coherence" is a useful heuristic to express how these different formal aspects of the mathematical structure of sociocultural phenomena are embedded in real-world material, spatiotemporal, cognitive, and communicative processes. A potentially guiding hypothesis is that the engines of structural coherence are the coupling processes of synchronization (see this question in Watts 1999a, 1999b) and bundling of tasks and activities—behaviorally, cognitively, and communicatively—within a field of social action.

[8]Ashby's law of requisite variety in representation, rephrased by Wilden (1987: 192), is that "the capacity of any system, R, to represent the diversity of another system, S, cannot exceed the flexibility of R as a coding system."

A goal related to the aforementioned one is to articulate this theory in terms of networked processes and emergent structures, with the seven patterns numbered in Table 1 (five of which are detailed in Table 2) constituting some of the principal formal patterns that require investigation. Some of the insights of complexity theory are articulated within this framework and generate the following heuristic hypotheses.

Structural Catalysis 1. Catalysis is regulation of processes through slowing down or speeding up their temporal rates or contracting/diffusing their temporal scales. Structural catalysis refers to the emergence of shared perception, language, and autoregulatory communication, which requires or presupposes the emergence of a perceptible formal pattern of a social field such as the five pattern principles in networks of relations. For Example, pattern 1 (**cohesion** measured by multiconnectivity; White and Harary 2001) is fundamental to the grouping principle. Pattern 2 (**balance** measured within partitions of connected networks; Harary 1953) is an essential basis for understanding exchange and conflict (Gregory 1982; White 2002, 2003). Pattern 3 (**small-world navigability**) is an essential principle of operational networks. Pattern 4 (**positional equivalence** and **analogy**; Lorrain 1974; Lorrain and White 1971) is fundamental to thought, narrative structure, the "situatedness" of intelligibility (Hofstadter, Dennett and Hofstadter 1985; Fauconnier 1997), and the recognition process in social identity, role, and attributed motivation and reputation (White 1992). Pattern 5 (**specialization** and **division of labor**) is the recognized basis of formal organizations, office holding, and the allocation of responsibility. Pattern 6 (**centralization**; Freeman 1979) is one of the modalities (see later discussion) by which other patterns are integrated.

Tipping Points. Tipping points (Gladwell 2000) occur in historical trajectories where, although networks are still composed of the same types of relations, the way that the relations are distributed across formal structural patterns (and functions) is dramatically altered. Pattern 7 (**distributed transformation**) is the result of reweighting of network elements—for example, the tipping of network structures into a redistribution of elements that may once have been centralized. Structural catalysis may alter which kinds of relations are utilized as the basis of grouping and/or as the basis of exchange. This occurs similarly for how relations are distributed in the logic of analogy/identity and the logic of allocation.

Table 2. Formal patterns in networks (as elements in the study of coherence)

	Pattern 1 Cohesive blocks	Pattern 2 Graph homomorphisms	Pattern 3 Small world	Pattern 4 Blockmodel (informal roles)	Pattern 5 Role structure (allocation)
Coherence	Group Blocking	Exchange opposition (balance, clustering)	Navigability over (small) distances	Analogous positions	Allocated positions
Relations	Multiple	Single	Single	Multiple	Tripartite*
–Within Sets	Connectivity	Disconnection	Clustering in subsets	Similarity	H × H social P × P formal T × T task seq.
–Between Sets	Inclusion	Connection	Reachability	Similarity	Bipartite maps
Structure	Hierarchy	Partition		Partition	H/T = H/P × P/T
Equivalence	(None: overlap)	Coloring	(None)	Regular	Multiple
Overlap	Minimum	None		None	
Reflexivity	n.a.	Disallowed	n.a.	Allowed	

*H = Humans, P = Positions, and T = Tasks (Oeser and Harary 1964, 1979).

Interdependence. Interdependence among the five pattern principles in Table 2 occurs in **pairings** (see Figure 1). The grouping logic of relational solidarity is paired with an exchange logic between groups (which are not, however, automatically solidary) and the analogous-positions logic in a behavioral system is paired with the formal or organizational activity allocation logic (but these two logics are not necessarily well coordinated). Pairing principles come out of balance theory as a principle of structural cohesion. Multilevel SW networks link and mediate these pairs.

Modalities. Modalities by which the pairs of pattern principles (1 and 2; 3 and 4) are articulated are segmentation (as in homomorphic equivalence classes) and cross-cutting integration (as in cohesive blocking and set intersection). Furthermore, if the pairings are in perfect alignment they are more likely to neatly **segment** and/or segregate a social field (and its perceptual and communicative superstructures); if they are in misalignment they **cross-cut** and thereby integrate a field through overlap, association, and attendant ambiguity.

Morphogenesis. Morphogenesis as an aspect of coherence results from the fact that the segmentary versus crosscut patterns, among others, have very different and very severe implications and consequences—they strongly affect the path dependence of evolution and historical trajectories. White (1969) established through comparative ethnographic analysis that morphogenic coherence occurs between the degree of crosscut integration in a social structure and the degree of cooperativity required in the labor processes. Grannis (1998) established the converse for urban systems: the greater the segmentation of transport and communication systems into treelike structures with cul-de-sacs, the lower the social integration and cooperativity, as measured by various indices.

Bundling. Bundling of activities in ways that satisfy easily executable behavioral routines is a necessary feature of spatiotemporal and socio-cognitive (shared information) systems. Goodenough (1963) develops this into a principle of cultural organization and dynamics. Morphogenic and network pattern principles come to bear on this fundamental organization problem. Coherence in the expressive behavior, because of activity and cognitive constraints similar to those that require bundling, also requires high coherence in coordinate mapping with the labor domain; hence the following.

Polarity Reduction. Polarity reduction occurs between activity and cognition, and between expressive and task behavior—one has only to see the films of Alan Lomax (1976) to recognize the coherence between them—as they are brought into coherent interdependence. In this process, for example, significant low-frequency activities (e.g., mortuary ceremonies) are brought into resonance or synchronization with high-frequency ones (e.g., daily or seasonally recurrent activities).

Structural Catalysis 2. Structural catalysis again (the emergence from a perceptible formal pattern of a field of perception, language, and autoregulatory communication) plays a role in bundling and polarity reduction. For example, analogous conceptual structures (pattern principle 4) map onto diverse activity sets and ‘‘unify’’ them culturally. Similarly, formal principles of political, organizational, and task allocation (pattern principle 5) require synchronization through structural catalysis of principles of recruitment, succession, and inheritance with activity and autoregulation processes.

1. From the smallest details up to the largest of abstract patterns of activity, **structural catalysis** is at work on different spatiotemporal and sociocognitive scales—that is, in a temporal and spatial spectrum, and in a social and cognitive spectrum of process. This is what dynamicists Iberall and Soodak (1978) call the stack of ‘‘factory day’’ processes that make up the spectra of activities of any complex system subject to near-equilibrium material and energetic constraints on repetitive activity cycles.
2. The two sets of pattern principles (1 and 2 versus 4 and 5) are articulated by dynamic mappings that involve further individuated network attributes such as centralities and diversity in other attributes that serve as the basis for recruitment and expulsion.
3. Within the group-level hierarchies of cohesion and adhesion there is room for further variability at the individual and subgroup levels including **centralization** and variability in relative centrality of nodes or subgroups (pattern 6). Centrality structures are constrained, however, by levels of cohesion. A star pattern of maximum centralization, for example, can occur where cohesion is low, whereas high cohesion places a limit on centralization.
4. In fluctuating environmental interactions, coherent systems may break up, and their resilient components reconfigure in **redistributed transformations** (pattern 7).

Measurement: Detecting Patterns in Networks

Cohesive blocking is a methodology recently refined by White and Harary (2001) that is crucial to theorizing about clusters of meaningfully related elements such as people in social groups, items in a material culture, or concepts in a symbolic world. A *k*-connected (or *k*-edge-connected) component in a graph of relationships is a maximal set of nodes in which no pair can be disconnected by removal of fewer than *k* nodes (or edges). Node versus edge connectivity defines cohesive and adhesive blocks in networks, respectively. A *k*-cohesive block is also a maximum set of nodes where every pair has *k* or more paths that are node independent (with no intermediate nodes in common). White and Newman (2001) give a fast algorithm to compute all such paths for large networks. The predictive consequences of measures of cohesion or adhesion for substantive variables in ethnographic and sociological studies have been shown for social class (Brudner and White 1997), leadership and group solidarity (Johansen and White 2002), group segmentation in conflict (White and Harary 2001) and attachment to school (Moody and White 2003), for example.

As shown in Table 2, while in cohesive blocking connections are grouped *within* sets, graph coloring is a homomorphism (generating color equivalence as a partition of nodes; edges can also be partitioned by similar principles) that goes in the opposite direction to observe the organization of equivalence sets when connections are limited to those *between* sets. Homomorphisms such as colorings are complementary to lattice structures (such as cohesive blocking hierarchies, which do not result in partitions) as principles in graph theory. Like colorings (and unlike cohesive blocks), block modeling (White et al.1976) is a homomorphism that generates a partition of nodes into nonoverlapping sets but without the constraints of graph colorings (which cannot put two connected nodes in the same equivalence set). Sociological block modeling (see also Lorrain and White 1971) is to the concept of *role* (analogous or similar position emerging out of a system of relations) what cohesive and adhesive blocking is to that of *group*. Table 2 shows some of the ways in which these approaches differ. Research remains to be done that will generalize cohesive blocking to the study of role structure as developed by Oeser and Harary (1964, 1979). This requires identifying tasks that cohere with one another, people who cohere with tasks, emergent roles and people that cohere with tasks, as well as formal roles that do so (algebraic products of people by positions and positions by tasks). No one as yet has shown how these different aspects of network modeling might be unified around an integrated sociocultural theory, mathematically well formulated, of the socially interactive basis of cognition and the coherence of human behavioral systems (see Goodenough 1963; Hutchins 1996; Moore 1998). At the mathematical level, the research steps needed to establish a common formal language for comparison and integration of the five approaches in the columns of Table 2 entail a formal restatement of each model in the common language of graph theory, and work on the formal conditional relationships amongst them (as has been done with connectivity and conditional density in developing the methodology of cohesive blocking). Also required, as discussed below, is the development of a substantive theoretical framework of hypotheses that allow us to measure and integrate the formal aspects or dimensions of these models in relation to empirically testable applications.

SOME RESEARCH PROBLEMS

Problem 1: **Cohesive unity.** What are the large as well as the smaller scale cohesive bases of cooperativity in social systems? What kinds of stable platforms for social, political and cultural organization (including knowledge bases) are formed on the basis of cohesive units? What kinds of factors affect the robustness and resilience of cohesive groups?

Problem 2: **Exchange balances and multilevel graphs.** Complementary to the formation of social, political, and territorial groups is the process of establishing exchange relationships between them. Unlike transactions carried out within a group, cross-boundary relations take on the possibility of exchange or opposition. Graph homomorphisms, like the coloring of territorial maps of polities, preserve the distinctness of groups connected by such cross-boundary edges. To our knowledge, the relationship between cohesive connectivity groups in networks (where the "positive" or in-group relations are of interest) and the partitioning or colorings of nodes by graph equivalence, where "negative" out-group or exchange relations are involved, has only begun to be studied (White and Harary 2001). This combined approach allows the study of competition and trade-offs between solidarity (in-group) and exchange (between group), and the emergence of complex divisions of labor induced by cohesive hierarchies. A key idea here is that cohesive groups are nested in hierarchies according to the degree of cohesion, so that exchange colorings may operate at different hierarchical levels. A second related idea is that the hierarchical or embedded relationship of different units or subgraphs is such that we may usefully consider modeling complex systems as multilevel graphs where lower order graphs are embedded in the nodes of higher order graphs (Harary and Batell 1981).

Problems 3 and 4: **Bundling and scaling**. When social, physical, and communicative processes are connected in a network in which costs and outcomes can be optimized under time and channel capacity constraints, small random or exploratory perturbations allow the material and energy allocations to drift toward an optimized network configuration. A structural prediction is that sequential sets of structurally equivalent nodes—connected to the same others—will tend to develop a coherently optimized role structure. Role structures become templates for organizing bundled sets of activities and actors and are extended in social and cognitive systems into analog (regular equivalence) models where the mapping of the template onto a new domain preserves the structure of linkages (White and Reitz 1983). Bundling principles provide dynamical processes partly responsible for construction of stable platforms or multiunit and multilevel systems of organization.

A second principle closely related to bundling in constructing multilevel platforms of network organization is that of *scaling*, which is related to the distribution of capacities of individual nodes and channels in a network in relation to the distribution of nodes and channels across a spatial or network topology. Biology has recently made massive progress with the scaling approach (West 1999). One of the key sociological insights of Powell et al. (2004), using this approach, is that the processes by which the network is populated with actors (recruitment, persistence, disappearance) and by which actors grow their links to others (e.g., individual-level decisions) tend to be determinant of the overall network topology (Albert and Barabási 2001).

Problem 5: **Distributive transformation**. The long-term longitudinal analysis of network structure and dynamics in relation to social and economic transformations is challenging but has high scientific payoffs in terms of understanding the linkages between structure and dynamics.

EXAMPLE

White and Houseman (2002) use many of the principles articulated here in their study of strong-tie navigable SW networks, such as the Arabic-type segmented lineage organization, in which different levels of intra-lineage as well as larger group cohesion are reinforced by endogamous marriages. For problems 1 and 2 they find that cohesion is distributed by intermarriage frequencies that distribute according to a $1/d^2$ power law decay that satisfies Kleinberg navigability in an SW network, where d is kinship distance. The multilevel network formed by marriages among lineage segments follows a strong-tie SW pattern, where the strong ties are those of reciprocal marriages between segments that are associated with intimacy and trust. For problems 3 and 4 they find a decentralized system in which problems of scaling responses to escalating conflictual or cooperative situations are bundled with the scaling of hierarchical lineage and larger societal segments that are cohesively reinforced by distance-decay marital ties. The social system they examine by use of longitudinal ethnographic network data has all the hallmarks of a self-organizing system. For problem 5, White and Johanson (2004) show that the robustness and leadership qualifications of this particular case are associated with successful families having large numbers of married children in which the historical demographics produce excess population exported to towns and cities, but changing marriage patterns of smaller in-dwelling-family sizes begin to undermine robustness in the contemporary period.

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