

Network Theories

Mark C. Pachucki

Department of Sociology & Computational Social Science Institute

University of Massachusetts, Amherst

mpachucki@umass.edu

Ronald L. Breiger

School of Sociology

University of Arizona

breiger@email.arizona.edu

1. Introduction: Three Traditions of Network Theory

Systematic research on the structuring of social relations—the analysis of social networks—has been increasing at an exponential rate in recent decades and has provided multiple foci of ever-expanding research interest across the social sciences as well as the biological and physical sciences and computational science (Borgatti and Halgin 2011). And yet, along with this explosive growth and many generative research contributions have come repeated charges that the field is atheoretical (reviewed in Erikson 2013, 219-220), and questioning of whether network theory has lived up to its promise (Galaskiewicz 2007). Indeed, an influential and highly-cited textbook on social network analysis (Wasserman and Faust 1994) is subtitled *Methods and Applications*, highlighting the aspects of social network analysis that many

Please cite as:

Pachucki, Mark C., Ronald Breiger. 2018. "Network Theories." Cambridge Handbook of Social Theory. Cambridge: Cambridge University Press. Forthcoming.

consumers as well as practitioners see as the major contributions of network studies, with scant mention of theoretical advances. We find three broad perspectives on theories of social networks to be helpful in organizing our thinking.

Model-Based Theory

The first broad perspective that we consider to be helpful in organizing our thinking about network theory emphasizes theory as rigorous formulations of social relations and social structure. In this sense the methods, applications, concepts and formal developments that have enabled the widely recognized scientific progress in network studies constitute in sum a highly significant, model-based theory. A non-exhaustive inventory of the most significant and highly influential contributions to this theory of networks would include the following: the distinction between strong and weak ties (the former tending to produce tightly connected clusters of actors but with clusters isolated from one another, while ties bridging clusters tend to be those of weak or specialized commitment), brokerage, centrality, transitivity of network connections, structural and more-generalized forms of equivalence (leading to identification of positions in networks on the basis of relational configurations), homophily (the principle that interpersonal networks may be and often are structured by similarities on the sociodemographic, behavioral, and intrapersonal characteristics of network actors), models of exchange networks (positing, for example, that the power of actor A over B is a function of resources that A controls and B desires), models for network structure arising from formal assumptions about actor rationality or strategy, models for multiple networks ranging from balance theory (for the interlinking of positive and negative affect) to role structures (algebraic modeling of rules for how different

types of networks interrelate), random graph models including small worlds (network models in which the distance between any pair of nodes is relatively short while transitivity or clustering is high), and scale-free networks (models for networks in which the distribution of the number of connections per node follows a mathematical power law, at least asymptotically). These innovations are reviewed in reference works in the social sciences (Borgatti, Everett, and Johnson 2018, De Nooy, Mrvar, and Batagelj 2011, Scott 2017, Wasserman and Faust 1994) including economics (Jackson 2008), in the biological sciences (Junker and Schreiber 2008), and in the physical and computational sciences (Newman 2010).

Ontological and Epistemological Underpinnings of Theory

A second perspective on network theory, in a sense the opposite of the first, emphasizes the articulation and development of thinking about the nature (ontology) of social networks, and the grounds for attaining knowledge about them (epistemology). Emirbayer's (1997) manifesto for a relational sociology focuses on ontology, by depicting the dilemma of "whether to conceive of the social world as consisting primarily in substances or processes" (281), "a choice of bedrock assumptions regarding the very nature of social reality itself" (311). The path an analyst chooses is consequential, for example, for whether the analyst conceptualizes "power" as a possession, something to be "seized" or "held" (p. 291), or in contrast chooses to analyze societies as "constituted of multiple overlapping and intersecting sociospatial networks of power" (Emirbayer quoting Mann 1986, p. 1). Martin (2009), in a book hailed as "the best work yet in network theory" (Collins 2013), takes as his central point "that certain relationships have inherent structural potentials" (Martin 2009, p. x). For example, the informal social relation of

patronage tends toward network connections in the layout of (hierarchical) trees, which can then serve as “the backbone for more deliberate governance structures” (p. 189). Reed (2017, 87), seeking an adequate analytical frame for the nature of power, puts forward “a basic theoretical vocabulary about power players and their projects.” For Reed, power as the capacity for action, “reached via the social and physical organization of persons into networks, depends on understanding and misunderstanding, signs of trust and interactive engagement, and thus on the modes of thought that imagine persons as actors in the first place” (p. 109). From the perspective on theory illustrated in this paragraph, the straightforward taking for granted of the existence of nodes (actors) and arcs (relations among nodes) that characterizes standard network analysis seems hopelessly naïve.

As an example of an intellectual movement within our second broad tradition, we consider the ontological and epistemological system of critical realism developed by philosopher Roy Bhaskar in collaboration with a number of British social theorists, including Margaret Archer (Gorski 2013). Smith (2011) provides an extended critique of what the author sees as the reductionism inherent in analytic and model-based network theories. Smith’s standpoint posits that a “*natural drive toward a sustained and thriving personal life broadly ... generates*” social structure (2011, 340, original italics). As Breiger and Puetz (2015) point out, Smith is sympathetic to the network structuralists’ rejection of the variables paradigm and Parsonsian theory. However, he portrays the pendulum as having swung too far, resulting in a network theory that is anti-humanist and person-annihilating. Smith (2011, 270, 272) argues that it is therefore necessary to redress network structuralism’s neglect of human dignity, rights, respect, and rational deliberation.

Analytical sociology (Hedström and Bearman 2009) provides another and quite different

example of an intellectual movement within our second broad tradition. Inasmuch as research on social networks guided by this approach has led to a great deal of model-based quantitative empirical research (Moody 2009), we were tempted to list analytical sociology under our first tradition. Nonetheless, analytical sociology emphasizes the ontological stance of individualism, as well as particular commitments to the concept of “mechanism” that “have more to do with philosophy of science than with sociology proper” (Hedström and Bearman 2009, 4). This approach to social networks highlights individual entities, the activities of those entities, and the patterns of relations among them in elucidating mechanisms that bring about social facts. Here, social facts are explained as the result of individuals’ actions, along with the social structures in which individuals are embedded (Hedström and Bearman 2009, Hedstrom and Ylikoski 2010, Pachucki, Jacques, and Christakis 2011).

Theory Beyond Networks

The third approach on network theory that we find helpful in organizing our thinking is that networks are not sufficient unto themselves for depicting the social world, but that theorization is required to understand how networks are implicated in a wide array of institutions, language(s), cultural practices, and social and geographic spaces, and that the structuring of network ties cannot be separated from the contents of network relations. In this way “network structure is one ingredient in a recipe that depends upon the presence and quality of several other ingredients” (Galaskiewicz 2007, 6). This third approach in a certain sense lies in between the other two, and in practice it often overlaps with one or (less commonly) both of them (i.e., with formal network analysis and / or explicitly ontological or epistemological

formulations). We expect two recent streams of work subsumed under this third approach to become particularly influential.

Lazega and colleagues have developed a distinctive neo-structural theoretical and empirical approach to networks and institutionalization (reviewed in Lazega 2017) that makes use of social and organizational network analyses, in combination with other methodologies, to better understand the roles of structure and culture in individual and collective agency. Lazega's neo-structural sociology (NSS) rests on theorization of multiple levels of agency and the problem of synchronization among levels (Lazega 2016) while revitalizing the study of Selznick's (1949) concerns about the design and governance of public institutions in a world "where an institution becomes a different thing to different people, and where each stakeholder pushes towards goal drift" (Lazega 2017, 13).

Padgett and Powell (2012), along with additional authors of several of the chapters comprising their book, exemplify our third tradition by having produced an analytic framework that spans historical research (fourteen case studies of the emergence of organizations and markets) and a modeling framework that applies concepts from biochemistry in order to understand the emergence of novelty in multiple domains (including language and national politics as well as markets and organizations). The authors view "inductive histories and deductive models ... as complementary (not competitive) research strategies" (2). Networks are central to the book's arguments about transformation, for example in its framing of organizational inventions as "transpositions of relational logics from one domain to another, which attain new purposes in the new domain, whose reproduction is positively reinforced to the point that it alters interactions among others in the new domain" (Padgett and Powell 2012, 201). Contrary to the approach of analytic sociology reviewed above, the mantra of Padgett and Powell

(p. 2) is that “in the short run, actors create relations; in the long run, relations create actors.”

Outline of the remainder of this chapter. In this review we seek to build upon the efforts described in this section and focus on more recent integrative relational theoretical efforts in two areas: relational approaches to networks and culture, and recent work at the interface of biological and social organization. Then we highlight current challenges and horizons for network theory, including temporality and dynamism in networks, networks and geography, the treatment of missing data, and network experiments. As network methods are increasingly important to parsing large amounts of information (i.e. “big data”), analytic efforts must be undertaken with care relative to local context and meaning (Bail 2014, Breiger 2015).

2. Relational approaches to network theory

The term “relational sociology” is itself highly contested (Dépelteau 2018). In one of its senses the key idea is that interaction settings include meaningful orientations among actors, whereas network analysis tends to explicitly ignore actors’ understandings in favor of a static and reductionist depiction of the nodes and network connections (Fine and Kleinman 1983). In relational network approaches, the meaning that one actor assigns to another is the basis for the relation, and in fact the absence of meaning could easily be understood as the absence of the relationship (Erikson 2013, 227). Thus, relational sociology analyzes networks as structures of relationships infused with meanings (Fuhse and Mützel 2010).

Although it is compelling and generative, the above conception omits recognition that the formal network modeling of Boorman and White (1976) had a different, but also valuable, approach to the study of meaning in networks, but at a different level: for Boorman and White,

the meaning of a type of tie (for example, advice-seeking) is given with respect to the patterning of its connections in comparison to the tie patterning in another type of network (for example, the network of friendship ties on the same population of actors). Moreover, the Boorman and White approach, but not the approach of relational sociology, is relevant to networks of impersonal interactions: for example, the network of world trade that takes nations as the nodes.

Nonetheless, in his book *Identity and Control* (White 1992 revised ed., 2008) Harrison White made clear that formal network models were necessary but not sufficient for answering the question of how social forms emerge, and that formal network analysis captures poorly the shifting meanings and the switchings of context that characterize social ties and bound them (Fontdevila 2018, 231). White's 1992 book upended existing formal network theory. As Fontdevila (2018, 236) relates, White now developed "story" as the subjective and phenomenological dimension of network tie. He now contended that "networks are phenomenological realities as well as measurement constructs," and he opposed the simplistic view of social networks as "physical monads" and "lines" in Cartesian space (White 1992, 65, quoted by Fontdevila 2018, 236).

During the 1980s and 1990s other scholars were articulating theories of networks and meaning, including Donati (see Donati 2018) and Emirbayer (1997; discussed earlier as a theorist of network ontology). In recent years, a number of scholars have identified productive tensions between relational theories of culture and networks (Mische 2011, Pachucki and Breiger 2010, Rule and Bearman 2015, Mohr and Rawlings 2015). This work focuses, e.g., on bridging oppositions such as meanings and structure; symbols and practices; and categorization and boundaries. The authors of the present chapter offered one such contribution in proposing the heuristic of "cultural holes" in an attempt to value the range of social meanings by which

individuals understand their lives and the patterns of connectivity and network position that mutually constitute social life (Pachucki and Breiger 2010). In this formulation, network structure is highly contingent on cultural context, and these entities co-evolve. Put another way, it is the constellation of cultural meanings, discourse, and practices that we suspect are most consequential in a particular actor occupying a structural position that bridges otherwise-disconnected network alters. Several empirical formalizations of this concept have recently been offered that extend our understanding of linkages between these realms.

As culture can be thought of in terms of similarities in communicative discourse, Vilhena and colleagues (2014) ambitiously analyzed the content of, and citation ties between, more than 1.5 million journal articles derived from 60 scientific fields contained in the JSTOR database between 1990 and 2010. Without shared culture and a common language, they posit, cultural holes exist between fields that impede the dissemination of ideas. Through the use topographical mapping, the authors quantified the semantic distance (e.g. the size of the cultural hole) between aggregate bodies of field-specific technical language. Doing so allows for visualization of the landscape of shared culture – an illustration that intuitively and usefully communicates, for instance, the width of the gap between social science discourse and biological jargon.

Another empirical examples illustrate different ways of bridging cultural forms and spanning cultural holes through a focus on cultural omnivorousness. Lizardo (2014), for instance, analyzed data from the Survey for Public Participation in the Arts with the use of two-mode network analysis methods to generate an index of the extent to which participants bridge musical and literary forms of culture. In doing so, Lizardo links one's propensity to bridge cultural holes with the notion of omnivorousness, and shows how previous measures of simple “omnivorousness by volume” (of distinct forms of culture) obscure the richness of actual patterns of cultural choice

that may constitute varieties of omnivorous consumption.

3. Network theories in biological and social organization

Across a broad number of social animal and insect species, network methods have been used to document fundamental aspects of sociability and social processes that lead to coordinated action to obtain food and build shelter for survival. The relative scarcity of cross-species comparative work (though see, e.g., Faust and Skvoretz 2002, Shizuka and McDonald 2012) highlights the difficulty of the task as well as the promise of such efforts for theory-building. As Charbonneau, Blonder, and Dornhaus (2013) describe, social insects such as ants, termites, bees, and wasps are ecologically successful because of their abilities to coordinate a division of labor. Like other biological networks, social insect networks have scale-free characteristics, exhibiting local clustering around distinct nodes, and a large proportion of nodes with few ties. Faust (2011) offers an especially insightful review of the expansive topic as animal social networks, especially given the challenge of the existence of tens of thousands of social animal species. Identifying cross-species variation and similarity can be useful in systematizing processes of dominance and hierarchy, social roles, preferential attachment, assortativity, kinship, and network temporal dynamics of stability and change. Pinter-Wollman et al. (2014) offer an important review of properties of animal social networks from a behavioral ecology perspective that views social interactions shaping not only group-level behaviors, but fundamentally affecting evolutionary fitness. The authors compare common analytical methods used to study different species, and describe meta-analytic efforts across species, as well as survey the state of network research on primates, ungulates, cetaceans, fish, and invertebrates. Importantly, they draw attention to the

need for studying the evolution of networks over time within-species, as well as cross-species comparisons with an eye towards temporal dynamics, tie definition, and public availability of data for replication by others.

Scientists have also begun to gain new traction on the questions of how sociability – and different network substructures – shape, and are shaped by, cognitive processes and brain function in humans. Brashears and Quintane (2015) enrolled several hundred undergraduate students to conduct an experiment of the recall of fictional friendship groupings. In contrast to a great deal of established wisdom, they found that individuals tend to encode cognitive networks of social ties at the triadic and more complex group levels, rather than relying upon recall of simpler dyadic ties. Because network recall affects how individuals act to make, maintain, and dissolve ties in the real world, this finding suggests that cognitive encoding heuristics may take priority over taste preferences in directing network processes. Techniques for studying cognitive localization such as functional MRI (fMRI) also show promise in studying the foundations of status processes in network settings. Zerubavel and colleagues (2015) studied collegiate members (n=26) of two identically-sized student voluntary organizations. Participants first rated sociometric popularity of other members, and then were shown pictures of members during fMRI scans, which tested for activation of the brain's social valuation system (ventromedial prefrontal cortex, ventral striatum, amygdala) and social cognition system (dorsomedial prefrontal cortex, temporoparietal junction, precuneus). Researchers found that sociometric popularity was differentially associated with activity in both of these cognitive systems. Additionally, mediation analysis showed that the social valuation system assumes a primary role, and that the valuation systems of popular participants were more sensitive to detection of status differences.

Further frontiers for network theorizing are the consideration of how social relationships with others – both perceived relationships as well as actual interactions – are fundamental to the human body’s health, subjective well-being, and cellular maintenance (Berkman and Krisha 2014, Holt-Lunstad and Smith 2016, Cole 2014). It is well-recognized from studies across the social sciences, and increasingly, the biological sciences, that different aspects of our social networks can affect the body’s function, and even our survival. For example, a meta-analysis of 148 studies that examined associations between structural and functional attributes of social network and mortality found that having more restricted networks on some dimension was linked with a 1.4-1.5 times greater mortality risk (Holt-Lunstad, Smith, and Layton 2010). The World Health Organization considers social support networks and culture as key social determinants of health (WHO 2018). Social scientists have identified a number of social-tie-related mechanisms that affect health outcomes, including social influence and social comparison, social control, having a sense of purpose and meaning, self-esteem, having a sense of mastery, belonging and companionship, and perceived social support (Thoits 2011). In addition, the structure of social ties can affect health behaviors over the life-course through the content of social ties and the meanings that individuals attribute and derive from actions, but also through a reciprocal interaction between mental health and the body’s physiological response (Umberson, Crosnoe, and Reczek 2010).

At the cellular level, one stream of research demonstrates the promise of using network tools to identify connectivity between different functional systems in the body. For instance, Goh et al. (2007) used bipartite graphs to generate a typology of human disease (the “diseaseome”) in which different forms of genetic disorder (e.g. Parkinson disease, Leukemia) are linked by a shared genetic mutations. This work provides a useful visual heuristic for examining genetic

links between disorders, with the promise of observing general patterns of disease that would not be possible to observe from discrete study of disorders alone. Even more granular than the genetic level, it is possible to examine how proteins within genes are interacting with one another. Menche and colleagues (2015) offer preliminary steps towards elaborating a complete map of this human “interactome”, and show how a network approach to examining overlapping neighborhoods of proteins reveals unexpected relationships between diseases at the molecular level. This form of research could enable discovery of how gene interactions cause a particular ailment. Practically speaking, disrupting one disease could disrupt the potential for another before symptoms are experienced by a patient or diagnosed by a physician.

Separately, research on social genomics that investigates relationships between one’s life circumstances and changes in gene expression illustrates how cells respond to socioenvironmental adversity and affect health and social behavior. Importantly, this work interrogates the roles that one’s social network plays as a part of the broader social environment. This type of research is an especially important frontier of theorizing network processes because it provides evidence of how social connectivity may “get under the skin” to affect biological mechanisms, and vice versa. Robinson, Fernald, and Clayton (2008) formulate a model of how, across a range of different species, social interactions shape the genome through complex behavioral, epigenetic, evolutionary, and developmental pathways. Focusing on humans, Steven Cole (2014) theorizes two processes - social signal transduction, in which networks shape gene expression through cascading biological pathways; and reciprocal recursion, in which gene expression feeds back to the function of the central nervous system to affect social behaviors and networks. As an example, Cole and colleagues (2011) studied gene expression in chronically lonely individuals, and found that specific immune cells (plasmacytoid dendritic cells,

monocytes, and B lymphocytes) mediate the effects of the social environment on immune function. Interestingly, gene expression was more strongly associated with subjective experiences of loneliness than one's actual social network size. This work suggests that the body's immune function has evolved in response to patterns of social interaction in order to reduce the likelihood of viral infection. Christakis and Fowler (2014) used genome-wide association study (GWAS) data to test a provocative hypothesis that humans tend to select friends with similar genotypes, theorizing that genetically similar friends might serve as a kind of functional kin. When they compared genotypes of friend pairs, they found these pairs to be more genetically similar than pairs of strangers. Friends are about as similar in terms of their genotype as 4th cousins are. Interestingly, the top quintile of single nucleotide polymorphisms (SNPs) shared by friends appear to have been more recently selected for by evolutionary processes, suggesting that friendship is evolutionarily adaptive for humans. Indeed, the interaction of social organization and culture at the locus of agriculture and diet has been shown through recent analysis of ancient DNA to influence evolutionary selection (Mathieson et al. 2015).

Further efforts to build models that integrate polygenic risk scores (Belsky and Israel 2014) derived from thousands to millions of SNPs related to a given trait can help us identify how genetic factors interact with behavioral and social processes involving social networks to determine later-life outcomes (Domingue et al. 2018).

4. Where theories of networks still struggle

In many ways, theories involving networks are no different than any other theoretical endeavor, insofar as testing, verification, building, and falsification are part of our collective

enterprise. However, several classes of problems that involve networks have been especially challenging, and we mention several persistently challenging concerns here.

Time and network evolution

One area where theories of networks could be meaningfully enriched is by according closer attention to different meanings and dimensions of time. During the past decade there has been a transition away from a prototypical longitudinal research design that may involve multiple panels at yearly or semi-regular intervals, and toward continuous data streams gathered at the scale of nanoseconds (in the case of cellular signaling), microseconds (online data streams), or seconds (human behavioral interactions). Truly impressive progress has been made concerning models and methods for the study of large temporal networks (Batagelj et al. 2014). However, analyzing network dynamics across multiple successive life-course periods has proven challenging (Pachucki and Goodman 2015, Kreager, Felmlee, and Alwin 2018). There have, of course, been exciting discoveries to emerge from large prospective cohort studies designed with a sociocentric focus such as Add Health (Bearman, Moody, and Stovel 2004, Domingue et al. 2018), or egocentric studies such as NSHAP (Cornwell et al. 2009). Other studies contain dyadic network information, such as the Framingham Heart Study (Christakis and Fowler 2007, Raghavan et al. 2016) or Health and Retirement Study (Yang et al. 2016). Such datasets have long provided a substrate for developing and testing network hypotheses. But our understanding of how affiliations or network processes at an earlier point in life may shape outcomes much later is necessarily impoverished because of a paucity of this form of data.

Networks and Place

It is the case that humans socially interact with others in geographic space, that network structures vary geographically, and that propinquity is a stronger determinant of social ties than connections with far-off people. The fundamental dependence of geography and sociability for information diffusion is implicit in experimental findings dating back to Travers and Milgram's classic work (1967) on the average path length of social networks using messages forwarded by the postal service (and updated for the digital age by Liben-Nowell and Kleinberg 2008, Liben-Nowell et al. 2005). Yet even in a sociocentric paradigm that bounds ties in a single space and theoretically controls for human movement, many analyses either ignore the spatial location of socially-connected individuals or include information about it while not fully accounting for the difficult statistical challenge of the correlated nature of geographical location. This is problematic because in dynamic systems, social ties, individual-level characteristics, human behaviors, and spatial location can change and interact on different timescales and in non-linear ways.

There are notable exceptions, and these theoretical and empirical lacunae have seen more attention in recent years. For one, research has revealed how physical location alone can be a proxy for sociability. Crandall et al. (2010) identified spatio-temporal co-occurrences based on over 85 million geo-tagged photographs, where a network tie was inferred between individuals based upon their precise location, and the inference of a tie was strengthened if there were multiple daily photographs at the shared location. Using mobile phone and texting data drawn from several million people in Europe, Onnela et al. (2011) also tested and confirmed that ties

were less likely with greater geographic distance, but additionally sought to test whether distance was associated with different features of group structure. The authors found that physical centrality was uncorrelated with betweenness centrality, and that small groups were cohesive in terms of spatial clustering and geographical span. Yet these geographical effects decayed as the group size grew to exceed 30 people. These findings suggest that scholars should pay more attention to the heterogeneity of geographical effects at different levels of social organization.

A more fundamental question concerns what the functional form of the dependence structure between distance and friendship looks like. To evaluate this question, Preciado et al. (2012) turned to a panel network study of several hundred seventh-graders in Sweden and used generalized additive models (GAMs) and logistic regression to model the form of distance dependence. These models confirmed that the likelihood of friendships decreased as the distance between two individuals increased in a logarithmic fashion. Then, the researchers integrated the functional form of distance dependence in stochastic actor-oriented models (SAOMs) that modeled friendships, individual characteristics, endogenous network effects, and distance simultaneously to show that geographic influence was independent of other effects. Yet separate research by Daraganova et al. (2012) among a suburban community of Australians modeled the simultaneous nature of network processes and geographic processes, and found that endogenous network processes were still at work even after adjusting for the effect of geographical proximity, which to the authors suggests a more limited influence of geographical proximity on network structures. Mathematically, this paper found that the functional form of the relationship between tie probability and distance was an “attenuated power law with baseline probability set to one”(2012, 16).

The idea that individuals may be nested in multiple types of social context is a difficult set of threads to disentangle. Evans et al. (2016) investigate how the sometimes overlapping social contexts of adolescents' schools, neighborhoods, and friendship networks can differentially contribute to variance in body-mass-index. Using Bayesian Markov Chain Monte Carlo (MCMC) cross-classified models, the authors find that adolescents' friendship network communities contribute far more to BMI than geographic location (neighborhoods or schools). It is also the case that structural properties of social networks can vary depending upon geographic location. Using a variety of simulation approaches, Butts et al. (2012) find that spatial variation is associated with network heterogeneity, but that certain network properties (aggregate mean degree, edge length, local clustering) can be ascertained by assessing geographic attributes of population size and land area within a given spatial context. As the authors eloquently put it, "...[network] subgraphs in a spatial context have a dual existence: they can be considered on the one hand in terms of their network properties, and on the other in terms of the spatial positions of their members" (p.94). It is our observation that scholars may productively benefit from giving greater analytic attention to this duality.

A further point at which network theories struggle has been highlighted by political and cultural geographers who have been working within place-based adaptations of post-structural, social constructivist, and actor-network theory (ANT) orientations. As the problem is described by Marshall and Staeheli (2015, 57), there seem to be "irreconcilable epistemological differences between the structuralist empiricism of quantitative, formal approaches using SNA and the post-structural constructivism of ANT and certain ethnographic approaches, which see networks as, in part, artefacts of the research process itself." Marshall and Staeheli present a tentative solution to this problem that involves iterative combinations of formal network visualization techniques and

ethnography. Using civil society organizations as their example, the authors produce a formal network visualization that is then used to raise the sort of critical questions (concerning, for example, how this structure came about) that cannot be answered by the formal network methods but that can be addressed by means of grounded ethnographic work.

Missing Data

Another persistent challenge in estimating properties of, and associations with, networks involves missing data. Relative to missing data approaches in survey research (Rubin and Little 2002), approaches for treating missing social network data for the purposes of causal inference are in their relative infancy, though this is starting to change (Handcock and Gile 2010, Robins, Pattison, and Woolcock 2004, Kossinets 2006, Koskinen, Robins, and Pattison 2010, Gile and Handcock 2017, Krause, Huisman, and Snijders 2018). Collecting complete data for social network analysis using survey approaches is a persistent challenge (Marsden 2005, Marin 2004, Marsden 2011). As a result, efforts often result in a substantial amount of missing data.

Missing network data present unique statistical challenges for causal inference because of the relational nature of the data. When a person (i.e. node) is missing, then relationships to others (i.e. social ties) can potentially be missing as well. Persons may be missing due to non-response, loss to follow-up, informant inaccuracy, or they may be missing by design due to the sampling strategy (Rubin and Little 2002). Relationship data may be missing due to boundary specification (non-inclusion of relevant nodes or ties) and censoring by node degree (produced by fixed-choice survey questions) (Faust 2008, Kossinets 2006).

A variety of approaches exist to sample network data, ranging from snowball sampling and link-tracing/respondent-driven sampling designs, to probabilistic models (Frank 2005, Marsden 2011, Chen, Crawford, and Karbasi 2015, Crawford, Wu, and Heimer 2015). There has been relatively little research to demonstrate how to infer a whole-network topology from incomplete network samples (Hanneke and Xing 2009). Currently, network approaches to remediate missing data include missing link prediction from attribute or structural information (Lü and Zhou 2011), network reconstruction of missing parts of networks (Guimerà and Sales-Pardo 2009), and network completion of missing nodes and ties (Kim and Leskovec 2011, Stork and Richards 1992). Limited evidence suggests that hierarchical structure can also be used to predict missing ties in partially observed networks (Clauset, Moore, and Newman 2008).

With respect to other of our outstanding questions, we do not know whether effects of missingness on health are consistent across the life course. It may be that a certain amount of missing network data in a sample of adolescents yields relatively unbiased estimates of peer effects on certain health outcomes, while the same amount of missing data in a sample of adults results in highly skewed estimates of that same outcome. One illustrative example concerns cardiovascular disease, which only begins to develop during early and middle adulthood. Because rates of cardiovascular diseases (CVD) are so low during adolescence, missing network data would likely have little bearing. However, among adults, the same amount of missing network data may result in seriously biased estimates of peer associations in CVD.

Network interventions & experiments

There are far more observational network studies than network-based interventions (Valente 2012). In sociocentric studies, this is typically because randomization encounters problems within a bounded community of individuals: many individuals tend to know one another. In studies of egocentric networks (or clusters of communities), there may be ties between clusters or between personal networks that interfere with appropriate discernment of the treatment effect (Staples, Ogburn, and Onnela 2015, VanderWeele, Ogburn, and Tchetgen Tchetgen 2012). Still, there is a growing literature on network experiments using Facebook or other social information platforms (Aral and Walker 2014, Bond et al. 2012, Kramer, Guillory, and Hancock 2014, Muchnik, Aral, and Taylor 2013, Phan and Airoidi 2015, Centola and Baronchelli 2015, Centola 2011), social games played by interacting participants (Han et al. 2017, Melamed, Simpson, and Harrell 2017, Nishi, Christakis, and Rand 2017, Shirado and Christakis 2017), primary schools (Paluck et al. 2016), Honduran villages (Kim et al. 2015), and Ugandan organizations (Baldassarri 2015) to discern mechanisms linking social relationships to a range of outcomes.

Klar and Shmargad (2017) study how network structure influences preference formation on public issues. To do so, they designed an experiment involving 348 subjects assigned randomly to one of two carefully-designed 144-person networks (plus 60 subjects in a control group): one a random network in which individuals reached others throughout the whole network with the same probability, the other a clustered lattice in which average path lengths were short and average distances between nodes in different regions of the network were long. Each person was by design connected to six others. Each network was designed to be like a social media network in that subjects received information about what their contacts were viewing. Information for and against two issues (GMO food and electric cars) was randomly seeded into

each network, with two individuals receiving a “dominant” opinion and one a “minority” or “underdog” opinion. On each of the experiment’s eight days, each subject received email notice of what information their contacts had viewed the day before, as information diffused through the networks. A basic finding was that “people connected to distant network regions [in the essentially random network] are exposed to dominant and underdog information at near equal rates” and, as a result, these subjects “learn about both sides of an issue and shift their attitudes toward the underdog.” Those in the clustered lattice network, where contacts tend to be confined to the same network region, on the other hand, tend to exhibit a single perspective (p. 717-718). Two additional rigorous examinations of the experimental findings were conducted: a simulation study, and three statistical analyses in which learning and support for the underdog were modeled. Given that the effects of network structure are difficult to locate with observational data, this study provides an exemplar of thoroughly rigorous research (experimental, simulation, and statistical) on how network structure affects preference formation.

5. Conclusions

As an aside, one final challenge posed by network theory is its resistance to being summarized succinctly in one handbook chapter! While researchers across the sciences and humanities (whether located in universities, government agencies, or the private sector) recognize the continued rapid acceleration of the rate of new empirical research publications on social networks, it is less appreciated that systematic theorization of social networks is also on the rise – and, we feel, more necessary than ever, given the increasingly interdisciplinary empirical study of social networks. We have endeavored to focus on the latter trend, emphasizing

developments and problems in network theory that we think deserve enhanced attention, though these are but selected examples. With the 2018 revision of the Federal Policy for the Protection of Human Subjects (the Common Rule), in some ways network research is poised to become more accessible than ever, yet must always be balanced against ever-present concerns about data privacy, respect for persons, beneficence, and justice in the pursuit of knowledge of the complexity of human relationships.

Acknowledgments

The authors would like to thank Chen-Shuo Hong for his research assistance on the topic of networks and geography.

References

- Aral, S., and D. Walker. 2014. "Tie Strength, Embeddedness, and Social Influence: A Large-Scale Networked Experiment." *Management Science* 60 (6):1352-1370.
- Bail, Christopher A. 2014. "The cultural environment: measuring culture with big data." *Theory and Society* 43 (3-4):465-482.
- Baldassarri, D. 2015. "Cooperative Networks: Altruism, Group Solidarity, Reciprocity, and Sanctioning in Ugandan Producer Organizations." *American Journal of Sociology* 121 (2):355-395.
- Batagelj, Vladimir, Patrick Doreian, Natasa Kejzar, and Anuska Ferligoj. 2014. *Understanding large temporal networks and spatial networks: Exploration, pattern searching, visualization and network evolution*. Vol. 2: John Wiley & Sons.
- Bearman, Peter S, James Moody, and Katherine Stovel. 2004. "Chains of affection: The structure of adolescent romantic and sexual networks." *American journal of sociology* 110 (1):44-91.
- Belsky, Daniel W, and Salomon Israel. 2014. "Integrating genetics and social science: Genetic risk scores." *Biodemography and social biology* 60 (2):137-155.
- Berkman, Lisa F., and Aditi Krishna. 2014. "Social Network Epidemiology." In *Social epidemiology*, edited by Lisa F. Berkman, Ichiro Kawachi and M. Maria Glymour, xvii, 615 pages. Oxford: Oxford University Press.
- Bond, R. M., C. J. Fariss, J. J. Jones, A. I. Kramer, C. Marlow, J. E. Settle, and J. H. Fowler. 2012. "A 61-million-person experiment in social influence and political mobilization." *Nature* 489 (7415):295-298.

- Boorman, S. A., and H. C. White. 1976. "Social-Structure from Multiple Networks .2. Role Structures." *American Journal of Sociology* 81 (6):1384-1446.
- Borgatti, S. P., and D. S. Halgin. 2011. "On Network Theory." *Organization Science* 22 (5):1168-1181.
- Borgatti, Stephen P., Martin G. Everett, and Jeffrey C. Johnson. 2018. *Analyzing social networks*. 2nd edition. ed. Los Angeles: SAGE.
- Brashears, M. E., and E. Quintane. 2015. "The microstructures of network recall: How social networks are encoded and represented in human memory." *Social Networks* 41:113-126.
- Breiger, Ronald L. 2015. "Scaling down." *Big Data & Society* 2 (2):2053951715602497.
- Breiger, Ronald L, and Kyle Puetz. 2015. "Culture and networks." *The International Encyclopedia of the Social and Behavioral Sciences*:557-62.
- Butts, C. T., R. M. Acton, J. R. Hipp, and N. N. Nagle. 2012. "Geographical variability and network structure." *Social Networks* 34 (1):82-100.
- Centola, D., and A. Baronchelli. 2015. "The spontaneous emergence of conventions: An experimental study of cultural evolution." *Proceedings of the National Academy of Sciences of the United States of America* 112 (7):1989-1994.
- Centola, Damon. 2011. "An experimental study of homophily in the adoption of health behavior." *Science* 334 (6060):1269-1272.
- Charbonneau, Daniel, Benjamin Blonder, and Anna Dornhaus. 2013. "Social insects: a model system for network dynamics." In *Temporal Networks*, 217-244. Springer.
- Chen, Lin, Forrest W Crawford, and Amin Karbasi. 2015. "Seeing the Unseen Network: Inferring Hidden Social Ties from Respondent-Driven Sampling." *arXiv preprint arXiv:1511.04137*.

- Christakis, N. A., and J. H. Fowler. 2007. "The spread of obesity in a large social network over 32 years." *New England Journal of Medicine* 357 (4):370-379.
- Christakis, N. A., and J. H. Fowler. 2014. "Friendship and natural selection." *Proc Natl Acad Sci U S A* 111 Suppl 3:10796-801.
- Clauset, Aaron, Cristopher Moore, and Mark EJ Newman. 2008. "Hierarchical structure and the prediction of missing links in networks." *Nature* 453 (7191):98-101.
- Cole, S. W. 2014. "Human social genomics." *PLoS Genet* 10 (8):e1004601.
- Cole, S. W., L. C. Hawkley, J. M. Arevalo, and J. T. Cacioppo. 2011. "Transcript origin analysis identifies antigen-presenting cells as primary targets of socially regulated gene expression in leukocytes." *Proc Natl Acad Sci U S A* 108 (7):3080-5.
- Collins, Randall. 2013. *Ten Major Theory Books Since 2000*. SAGE Publications Sage CA: Los Angeles, CA.
- Cornwell, Benjamin, L Philip Schumm, Edward O Laumann, and Jessica Graber. 2009. "Social Networks in the NSHAP Study: rationale, measurement, and preliminary findings." *Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 64 (suppl_1):i47-i55.
- Crandall, D. J., L. Backstrom, D. Cosley, S. Suri, D. Huttenlocher, and J. Kleinberg. 2010. "Inferring social ties from geographic coincidences." *Proceedings of the National Academy of Sciences of the United States of America* 107 (52):22436-22441.
- Crawford, Forrest W, Jiacheng Wu, and Robert Heimer. 2015. "Hidden population size estimation from respondent-driven sampling: a network approach." *arXiv preprint arXiv:1504.08349*.

Daraganova, G., P. Pattison, J. Koskinen, B. Mitchell, A. Bill, M. Watts, and S. Baum. 2012.

"Networks and geography: Modelling community network structures as the outcome of both spatial and network processes." *Social Networks* 34 (1):6-17.

De Nooy, Wouter, Andrej Mrvar, and Vladimir Batagelj. 2011. *Exploratory social network analysis with Pajek*. Vol. 27: Cambridge University Press.

Dépelteau, François. 2018. *The Palgrave handbook of relational sociology*: Springer.

Domingue, Benjamin W, Daniel W Belsky, Jason M Fletcher, Dalton Conley, Jason D

Boardman, and Kathleen Mullan Harris. 2018. "The social genome of friends and schoolmates in the National Longitudinal Study of Adolescent to Adult Health."

Proceedings of the National Academy of Sciences:201711803.

Donati, Pierpaolo. 2018. "An Original Relational Sociology Grounded in Critical Realism." In

The Palgrave Handbook of Relational Sociology, 431-456. Springer.

Emirbayer, M. 1997. "Manifesto for a relational sociology." *American Journal of Sociology* 103 (2):281-317.

Erikson, E. 2013. "Formalist and Relationalist Theory in Social Network Analysis."

Sociological Theory 31 (3):219-242.

Evans, C. R., J. P. Onnela, D. R. Williams, and S. V. Subramanian. 2016. "Multiple contexts and

adolescent body mass index: Schools, neighborhoods, and social networks." *Social Science & Medicine* 162:21-31.

Faust, K., and J. Skvoretz. 2002. "Comparing networks across space and time, size and species."

Sociological Methodology 2002, Vol 32 32:267-299.

Faust, Katherine. 2008. "Triadic configurations in limited choice sociometric networks:

empirical and theoretical results." *Social Networks* 30 (4):273-282.

- Faust, Katherine. 2011. "Animal Social Networks." In *The SAGE handbook of social network analysis*, edited by John Scott and Peter J Carrington. SAGE publications.
- Fine, Gary Alan, and Sherryl Kleinman. 1983. "Network and meaning: An interactionist approach to structure." *Symbolic interaction* 6 (1):97-110.
- Fontdevila, Jorge. 2018. "Switchings Among Netdoms: The Relational Sociology of Harrison C. White." In *The Palgrave Handbook of Relational Sociology*, 231-269. Springer.
- Frank, Ove. 2005. "Network sampling and model fitting." In *Models and methods in social network analysis*, edited by PJ Carrington, J Scott and S Wasserman, 31-56.
- Fuhse, Jan, and Sophie Mützel. 2010. *Relationale Soziologie*. Vol. 2: Springer-Verlag.
- Galaskiewicz, Joseph. 2007. "Has a Network Theory of Organizational Behaviour Lived Up to its Promises?" *Management and Organization Review* 3 (1):1-18.
- Gile, Krista J, and Mark S Handcock. 2017. "Analysis of networks with missing data with application to the National Longitudinal Study of Adolescent Health." *Journal of the Royal Statistical Society: Series C (Applied Statistics)* 66 (3):501-519.
- Goh, K. I., M. E. Cusick, D. Valle, B. Childs, M. Vidal, and A. L. Barabasi. 2007. "The human disease network." *Proc Natl Acad Sci U S A* 104 (21):8685-90.
- Gorski, Philip S. 2013. *What is critical realism? And why should you care?* : SAGE Publications Sage CA: Los Angeles, CA.
- Guimerà, Roger, and Marta Sales-Pardo. 2009. "Missing and spurious interactions and the reconstruction of complex networks." *Proceedings of the National Academy of Sciences* 106 (52):22073-22078.

Han, X., S. N. Cao, Z. S. Shen, B. Y. Zhang, W. X. Wang, R. Cressman, and H. E. Stanley.

2017. "Emergence of communities and diversity in social networks." *Proceedings of the National Academy of Sciences of the United States of America* 114 (11):2887-2891.

Handcock, Mark S, and Krista J Gile. 2010. "Modeling social networks from sampled data." *The Annals of Applied Statistics* 4 (1):5-25.

Hanneke, Steve, and Eric P Xing. 2009. "Network completion and survey sampling."

International Conference on Artificial Intelligence and Statistics.

Hedstrom, P., and P. Ylikoski. 2010. "Causal Mechanisms in the Social Sciences." *Annual Review of Sociology, Vol 36* 36:49-67.

Hedström, Peter, and Peter S. Bearman. 2009. *The Oxford handbook of analytical sociology, Oxford handbooks*. Oxford ; New York: Oxford University Press.

Holt-Lunstad, J., T. B. Smith, and J. B. Layton. 2010. "Social Relationships and Mortality Risk: A Meta-analytic Review." *Plos Medicine* 7 (7).

Holt-Lunstad, Julianne, and Timothy B Smith. 2016. "Loneliness and social isolation as risk factors for CVD: implications for evidence-based patient care and scientific inquiry." *Heart:heartjnl-2015-309242*.

Jackson, Matthew O. 2008. "Social networks in economics." *Handbook of Social Economics, J. Benhabib, A. Bisin, and MO Jackson, Eds., New York: Elsevier*.

Junker, BH, and F Schreiber. 2008. "Correlation networks." *Analysis of Biological Networks*.

Kim, D. A., A. R. Hwang, D. Stafford, D. A. Hughes, A. J. O'Malley, J. H. Fowler, and N. A.

Christakis. 2015. "Social network targeting to maximise population behaviour change: a cluster randomised controlled trial." *Lancet* 386 (9989):145-153.

- Kim, Myunghwan, and Jure Leskovec. 2011. "The Network Completion Problem: Inferring Missing Nodes and Edges in Networks." *SDM*.
- Klar, S., and Y. Shmargad. 2017. "The Effect of Network Structure on Preference Formation." *Journal of Politics* 79 (2):717-721.
- Koskinen, Johan H, Garry L Robins, and Philippa E Pattison. 2010. "Analysing exponential random graph (p-star) models with missing data using Bayesian data augmentation." *Statistical Methodology* 7 (3):366-384.
- Kossinets, Gueorgi. 2006. "Effects of missing data in social networks." *Social networks* 28 (3):247-268.
- Kramer, A. D. I., J. E. Guillory, and J. T. Hancock. 2014. "Experimental evidence of massive-scale emotional contagion through social networks." *Proceedings of the National Academy of Sciences of the United States of America* 111 (24):8788-8790.
- Krause, Robert W, Mark Huisman, and Tom AB Snijders. 2018. "Multiple imputation for longitudinal network data." *Italian Journal of Applied Statistics forthcoming*.
- Kreager, Derek A, Diane H Felmlee, and Duane F Alwin. 2018. "Strategies for Integrating Network and Life Course Perspectives." In *Social Networks and the Life Course*, 479-486. Springer.
- Lazega, Emmanuel. 2016. "Synchronization costs in the organizational society: Intermediary relational infrastructures in the dynamics of multilevel networks." In *Multilevel Network Analysis for the Social Sciences*, edited by Emmanuel Lazega and Tom A. B. Snijders, 47-77. Cham, Switzerland: Springer.
- Lazega, Emmanuel. 2017. "Networks and Institutionalization: A Neo-structural Approach." *Connections* (37):7-22.

- Liben-Nowell, D., and J. Kleinberg. 2008. "Tracing information flow on a global scale using Internet chain-letter data." *Proceedings of the National Academy of Sciences of the United States of America* 105 (12):4633-4638.
- Liben-Nowell, D., J. Novak, R. Kumar, P. Raghavan, and A. Tomkins. 2005. "Geographic routing in social networks." *Proceedings of the National Academy of Sciences of the United States of America* 102 (33):11623-11628.
- Lizardo, O. 2014. "Omnivorousness as the bridging of cultural holes: A measurement strategy." *Theory and Society* 43 (3-4):395-419.
- Lü, Linyuan, and Tao Zhou. 2011. "Link prediction in complex networks: A survey." *Physica A: Statistical Mechanics and its Applications* 390 (6):1150-1170.
- Marin, Alexandra. 2004. "Are respondents more likely to list alters with certain characteristics?: Implications for name generator data." *Social Networks* 26 (4):289-307.
- Marsden, Peter V. 2005. "Recent developments in network measurement." *Models and methods in social network analysis* 8:30.
- Marsden, Peter V. 2011. "Survey methods for network data." *The SAGE handbook of social network analysis*:370-388.
- Marshall, David J, and Lynn Staeheli. 2015. "Mapping civil society with social network analysis: Methodological possibilities and limitations." *Geoforum* 61:56-66.
- Martin, John Levi. 2009. *Social structures*: Princeton University Press.
- Mathieson, I., I. Lazaridis, N. Rohland, S. Mallick, N. Patterson, S. A. Roodenberg, E. Harney, K. Stewardson, D. Fernandes, M. Novak, K. Sirak, C. Gamba, E. R. Jones, B. Llamas, S. Dryomov, J. Pickrell, J. L. Arsuaga, J. M. de Castro, E. Carbonell, F. Gerritsen, A. Khokhlov, P. Kuznetsov, M. Lozano, H. Meller, O. Mochalov, V. Moiseyev, M. A.

- Guerra, J. Roodenberg, J. M. Verges, J. Krause, A. Cooper, K. W. Alt, D. Brown, D. Anthony, C. Lalueza-Fox, W. Haak, R. Pinhasi, and D. Reich. 2015. "Genome-wide patterns of selection in 230 ancient Eurasians." *Nature*.
- Melamed, D., B. Simpson, and A. Harrell. 2017. "Prosocial Orientation Alters Network Dynamics and Fosters Cooperation." *Scientific Reports* 7.
- Menche, J., A. Sharma, M. Kitsak, S. D. Ghiassian, M. Vidal, J. Loscalzo, and A. L. Barabasi. 2015. "Disease networks. Uncovering disease-disease relationships through the incomplete interactome." *Science* 347 (6224):1257601.
- Mische, Ann. 2011. "Relational sociology, culture, and agency." *The Sage handbook of social network analysis*:80-97.
- Mohr, John W., and Craig Rawlings. 2015. Formal Methods of Cultural Analysis. In *International Encyclopedia of the Social & Behavioral Sciences*, edited by James D. Wright: Elsevier.
- Moody, James. 2009. "Network dynamics." *The oxford handbook of analytical sociology*:447-474.
- Muchnik, L., S. Aral, and S. J. Taylor. 2013. "Social Influence Bias: A Randomized Experiment." *Science* 341 (6146):647-651.
- Newman, Mark. 2010. *Networks: an introduction*: Oxford university press.
- Nishi, A., N. A. Christakis, and D. G. Rand. 2017. "Cooperation, decision time, and culture: Online experiments with American and Indian participants." *Plos One* 12 (2).
- Onnela, J. P., S. Arbesman, M. C. Gonzalez, A. L. Barabasi, and N. A. Christakis. 2011. "Geographic Constraints on Social Network Groups." *Plos One* 6 (4).

- Pachucki, M. A., and R. L. Breiger. 2010. "Cultural Holes: Beyond Relationality in Social Networks and Culture." *Annual Review of Sociology*, Vol 36 36:205-224.
- Pachucki, M. A., P. F. Jacques, and N. A. Christakis. 2011. "Social Network Concordance in Food Choice Among Spouses, Friends, and Siblings." *American Journal of Public Health* 101 (11):2170-2177.
- Pachucki, Mark C, and Elizabeth Goodman. 2015. "Social relationships and obesity: Benefits of incorporating a lifecourse perspective." *Current Obesity Reports*:1-7.
- Padgett, John F, and Walter W Powell. 2012. *The emergence of organizations and markets*: Princeton University Press.
- Phan, T. Q., and E. M. Airoidi. 2015. "A natural experiment of social network formation and dynamics." *Proceedings of the National Academy of Sciences of the United States of America* 112 (21):6595-6600.
- Pinter-Wollman, N., E. A. Hobson, J. E. Smith, A. J. Edelman, D. Shizuka, S. de Silva, J. S. Waters, S. D. Prager, T. Sasaki, G. Wittemyer, J. Fewell, and D. B. McDonald. 2014. "The dynamics of animal social networks: analytical, conceptual, and theoretical advances." *Behavioral Ecology* 25 (2):242-255.
- Preciado, P., T. A. B. Snijders, W. J. Burk, H. Stattin, and M. Kerr. 2012. "Does proximity matter? Distance dependence of adolescent friendships." *Social Networks* 34 (1):18-31.
- Raghavan, S., M. C. Pachucki, Y. C. Chang, B. Porneala, C. S. Fox, J. Dupuis, and J. B. Meigs. 2016. "Incident Type 2 Diabetes Risk is Influenced by Obesity and Diabetes in Social Contacts: a Social Network Analysis." *Journal of General Internal Medicine* 31 (10):1127-1133.

- Reed, Isaac Ariail. 2017. "Chains of Power and Their Representation." *Sociological Theory* 35 (2):87-117.
- Robins, Garry, Philippa Pattison, and Jodie Woolcock. 2004. "Missing data in networks: exponential random graph (p^*) models for networks with non-respondents." *Social Networks* 26 (3):257-283.
- Robinson, Gene E, Russell D Fernald, and David F Clayton. 2008. "Genes and social behavior." *science* 322 (5903):896-900.
- Rubin, Donald B, and Roderick JA Little. 2002. "Statistical analysis with missing data." *Hoboken, NJ: J Wiley & Sons.*
- Rule, Alix, and Peter Bearman. 2015. "Networks and culture." *Routledge International Handbook of the Sociology of Art and Culture*:161.
- Scott, John. 2017. *Social network analysis*: Sage.
- Selznick, Philip. 1949. *TVA and the grass roots: A study in the sociology of formal organization*. Vol. 3: Univ of California Press.
- Shirado, H., and N. A. Christakis. 2017. "Locally noisy autonomous agents improve global human coordination in network experiments." *Nature* 545 (7654):370-+.
- Shizuka, D., and D. B. McDonald. 2012. "A social network perspective on measurements of dominance hierarchies." *Animal Behaviour* 83 (4):925-934.
- Smith, Christian. 2011. *What is a person?: Rethinking humanity, social life, and the moral good from the person up*: University of Chicago Press.
- Staples, P. C., E. L. Ogburn, and J. P. Onnela. 2015. "Incorporating Contact Network Structure in Cluster Randomized Trials." *Sci Rep* 5:17581.

- Stork, Diana, and William D Richards. 1992. "Nonrespondents in Communication Network Studies Problems and Possibilities." *Group & Organization Management* 17 (2):193-209.
- Thoits, P. A. 2011. "Mechanisms linking social ties and support to physical and mental health." *J Health Soc Behav* 52 (2):145-61.
- Travers, Jeffrey, and Stanley Milgram. 1967. "The small world problem." *Psychology Today* 1 (1):61-67.
- Umberson, D., R. Crosnoe, and C. Reczek. 2010. "Social Relationships and Health Behavior Across the Life Course." *Annual Review of Sociology, Vol 36* 36:139-157.
- Valente, T. W. 2012. "Network interventions." *Science* 337 (6090):49-53.
- VanderWeele, T. J., E. L. Ogburn, and E. J. Tchetgen Tchetgen. 2012. "Why and When "Flawed" Social Network Analyses Still Yield Valid Tests of no Contagion." *Stat Politics Policy* 3 (1):2151-1050.
- Vilhena, Daril A, Jacob G Foster, Martin Rosvall, Jevin D West, James Evans, and Carl T Bergstrom. 2014. "Finding cultural holes: how structure and culture diverge in networks of scholarly communication." *Sociological Science* 1:221-238.
- Wasserman, Stanley, and Katherine Faust. 1994. *Social network analysis: Methods and applications*. Vol. 8: Cambridge university press.
- White, Harrison C. 1992. *Identity and control : a structural theory of social action*. Princeton, N.J.: Princeton University Press.
- White, Harrison C. 2008. *Identity and control : how social formations emerge*. 2nd ed. Princeton: Princeton University Press.

WHO. 2018. "The determinants of health." World Health Organization, accessed June 29, 2018.

<http://www.who.int/hia/evidence/doh/en/>.

Yang, Y. C., C. Boen, K. Gerken, T. Li, K. Schorpp, and K. M. Harris. 2016. "Social relationships and physiological determinants of longevity across the human life span." *Proceedings of the National Academy of Sciences of the United States of America* 113 (3):578-583.

Zerubavel, N., P. S. Bearman, J. Weber, and K. N. Ochsner. 2015. "Neural mechanisms tracking popularity in real-world social networks." *Proc Natl Acad Sci U S A* 112 (49):15072-7.