Social Network Analysis in Archaeology
Author(s): Barbara J. Mills
Source: *Annual Review of Anthropology*, Vol. 46 (2017), pp. 379-397
Published by: Annual Reviews
Stable URL: https://www.jstor.org/stable/44866096
Accessed: 03-06-2025 14:07 UTC

Social Network Analysis in Archaeology

Barbara J. Mills

School of Anthropology, University of Arizona, Tucson, Arizona 85721-0030;
email: bmills@email.arizona.edu

Annu. Rev. Anthropol. 2017. 46:379–97

First published as a Review in Advance on August 7, 2017

The *Annual Review of Anthropology* is online at anthro.annualreviews.org

https://doi.org/10.1146/annurev-anthro-102116-041423

Keywords

social network analysis, archaeological networks, relational archaeology, spatial analysis, complexity

Abstract

Social network analysis (SNA) in archaeology has become important for a range of theoretical and methodological approaches that can more generally be characterized as relational. They are relational in that it is the ties between actors (or nodes) that define social connections. Archaeologists are currently employing a diversity of theoretical approaches to networks, and the perspective taken in this review is that SNA can provide insights into a number of different social processes using different theories. Following a brief historical overview, I discuss two aspects of SNA: the structural position of the actor or node, and characterizations of whole networks. I then summarize several broad classes of archaeological networks: historical, spatial, and material. I conclude with a call for more bridging approaches to span alternative theoretical and methodological approaches in the archaeology of networks.

INTRODUCTION

Small-world model: a few random ties can reduce overall average path length in networks of mostly local ties

Graph theory: the mathematical study of a set of points (nodes) and lines (arcs) that model pairwise relationships in a network

Network approaches in archaeology have increased exponentially over the past two decades (Collar et al. 2015, figure 1), producing a diverse body of scholarship that is, by its nature, relational and interdisciplinary. These approaches are relational because they focus on the connections or ties that connect entities—known as nodes, vertices, or actors—rather than the entities themselves. The ties may represent different kinds of social relations, ranging from economic transactions to shared identities and other affiliations. Network approaches are interdisciplinary in that they draw on a wider literature that crosscuts fields as diverse as computer sciences, physics, life sciences, digital humanities, and the social sciences (Newman 2010). This interdisciplinarity makes network approaches appealing because they can be used by teams of researchers from different fields and with different theoretical stances. The interdisciplinary nature of network analyses requires knowledge of a breadth of method and theory, however, and the future of network applications in archaeology clearly depends on both understanding what is being done in other fields as well as forging new analyses, collaborations, and insights matched to archaeological questions and data.

Archaeological applications of network approaches range from research on the relationality of humans and things within broader studies of materiality (e.g., Hodder & Mol 2016, Knappett 2011) to complexity studies, with an emphasis on nonlinear systems and their transformation over time (Cegielski & Rogers 2016). Formal applications in archaeology largely draw on social network analysis (SNA), which is composed of methods and theories that were developed in sociology and sociocultural anthropology. In this review, I emphasize archaeologists' use of SNA and argue that one of the strengths of formal analyses is that they can be incorporated into research using different theoretical standpoints to look at how actors structure networks and networks structure interactions among actors. However, more work is currently needed on bridging network theory—a vibrant and emerging interdisciplinary paradigm—with social theory.

HISTORICAL OVERVIEW

Present-day applications of network approaches developed in a number of disciplines. Brughmans's (2010 figure 1; see also Brughmans 2012, 2013a, 2014; Brughmans & Peeples 2017) network analyses of citations in publications on archaeological networks show that there is not a single intellectual ancestor. Rather, present-day archaeological use of SNA derives from heterogeneous sources, including anthropology, sociology, geography, computer sciences, and physics. Recent works often do not cite one another, suggesting that there are distinctive communities of practice. The small-world model of physics and computer sciences (Watts & Strogatz 1998) was an important inspiration. Another strand has come out of formal analyses in sociology and anthropology, which drew on graph theory with its attention to entities and the connections between them (Harary 1969, Wasserman & Faust 1994). Even metaphorical usages of networks in archaeology (e.g., Malkin 2011) draw on formal network analysis concepts.

Freeman (2004, p. 3) notes that all four components of SNA were in place by the mid-1900s: (*a*) a proposal that the structure of ties between actors or nodes is consequential, (*b*) inclusion of systematic compilation of empirical data, (*c*) use of graphs or other visualizations, and (*d*) application of mathematical or computational models. In anthropology, social network theory was used by the Manchester School and applied to kinship and exchange from the 1950s through the 1970s (e.g., Barnes 1954). Although many ethnographers continued to use formal network techniques (e.g., Hage & Harary 1996), SNA did not take as firm a hold in sociocultural anthropology as it did in sociology.

The adoption of poststructuralism in anthropology led to large-scale rejection of many formal, quantitative analyses by anthropologists—including SNA. As with the topics of migration, kinship, and diffusion, the turn away from SNA may be seen as an example of throwing the baby out with the bathwater (cf. Anthony 1990). The infancy of a relational, structural approach without agency, practice, or meaning placed SNA outside of mainstream anthropological analyses—including archaeology—even as use of network metaphors and other relational approaches increased in archaeology (e.g., Hutson 2010, Watts ed. 2013). This situation is now changing as a network paradigm becomes more widely employed and as both structure and agency are more fully incorporated (cf. Schortman 2014).

The earliest archaeological applications of SNA drew on spatial approaches in geography (e.g., Chorley & Haggett 1967) and graph theory (Harary 1969), treating regional settlements as nodes. Irwin-Williams (1977) developed a perceptive research design for the Chaco region of the U.S. Southwest that defined monumental structures as nodes and proposed that interactions between nodes could be based on artifact provenance analyses. Island archaeologists, in particular, looked at maritime spatial networks through proximal point analysis (PPA), represented as a graph (Broodbank 1993, Davis 1982, Hunt 1988, Terrell 1977). Rothman (1987) applied graph theory to the regional distribution of settlements on the Susiana Plain and then compared these to the ratio of beveled rim bowls to other ceramics in order to identify Uruk administrative reach. Another early adopter was Peregrine (1991), who applied graph analysis to Cahokia, demonstrating that it was located in the most spatially centralized spot along the Mississippi River and its tributaries. The major problem with PPA in light of current SNA methods is that it connects each node with its nearest neighbor but does not build connections between nodes that are not neighbors (Östborn & Gerding 2014).

The explicit incorporation of theories of relationality and meaning is one of the most important changes that has occurred in the use of SNA in archaeology. Knappett's (2011) book, *An Archaeology of Interaction*, was a turning point for many archaeologists in the linking of social networks, practice theory, and materiality because he was able to show how all of these concepts intersect. As his volume also points out, much of the success of SNA in archaeology has been at the regional level, but the linkages are in communities of practice (Lave & Wenger 1991) that operate at smaller social scales and are reproduced or accumulated at larger historical and spatial scales.

Another important factor propelling the use of SNA in archaeology is that networks are complex systems. Inspiration for archaeologists lies in the commonalities with other disciplines looking at complexity, including physics and computer sciences (Mitchell 2006). There are many strands of complexity research in archaeology, and SNA has been used in both empirical and experimental contexts—the latter largely through computer simulations.

Methodological advances have also played a part in SNA's popularity in archaeology. Three stand out: (*a*) the ability to handle large data sets; (*b*) complementarity with other suites of analytical techniques, especially geographic information systems (GIS) and agent-based models (ABMs); and (*c*) tools for producing complex computer visualizations of networks. The latter are particularly useful for exploratory data analysis and public outreach.

Today, there are international, often multidisciplinary, communities of network analysts who work on archaeological problems and data. Conferences that explore the intersections of experimental and empirical analyses, actor–network theory and SNA, and spatial and social approaches are increasing (see Lock & Pouncett 2007 for an early integration of SNA and GIS). If anything, the field has opened up considerably, and there is a healthy eclecticism as shown by the papers in several recent books and special journal issues (Brughmans et al. 2016, Collar et al. 2015, Evans & Felder 2014, Knappett 2013). This is hardly "anything goes," however, and many archaeologists are intensively engaged in refining network methods (e.g., papers in Collar et al. 2015, Östborn & Gerding 2014, Peeples & Roberts 2013). Much of this work is done collaboratively among teams of scholars, creating, on the one hand, a set of well-defined terms and analytical procedures and, on the other hand, challenges because of different disciplinary histories and semantics.

Weak tie: ties that are socially distant that may link otherwise unconnected subgroups (i.e., high betweenness centrality)

Centrality: a set of measures that summarize the ranked position of a particular node in relation to other nodes in the network

Density of ties: the ratio of the actual number of ties to the number of all possible ties

Cohesion: the extent to which nodes are interconnected, as indicated by high global (over the whole network) or local (in a subgroup) density

Component: a maximal subgroup in which there are either direct ties or paths between all pairs of nodes

Power law: a mathematical function often used to model preferential attachment and identification of hubs (nodes with many ties)

Preferential attachment: the likelihood that hubs with many connections will attract more ties

TWO APPROACHES TO NETWORK THEORY: NODE POSITION AND OVERALL NETWORK STRUCTURE

Within the general field of SNA, there are two complementary ways to characterize network properties, each of which has associated theories of how networks work: the position of nodes and overall network structure (Borgatti & Halgin 2011). Node position refers to how the location of the node within the network influences the behavior and future of that node. An example of this view is the strength of weak ties (Granovetter 1983) in which nodes that are positioned between two otherwise unconnected nodes have enhanced access to information and resources from other parts of the network. A related theory is that of brokerage, which Stovel & Shaw (2012, p. 140) define as "one of a small number of mechanisms by which disconnected or isolated individuals (or groups) can interact economically, politically, and socially." Peeples & Haas (2013) have the most explicit application of brokerage to archaeology; they point out that there is a range of possible outcomes for those in broker positions depending on the nature of information and resources being shared. Cultural factors may tamp down or elevate those who make use of the information or resources—and these have implications for the persistence of nodes over time.

Other examples of node position relate to how central a node is in the network. Centrality has been one of the most prominent ways for measuring nodal properties in archaeology, but it is also a theoretical construct about how the node interacts with other nodes and its potential when viewed dynamically. Centrality is often thought of as a person or group with more social prominence. Because there are a number of different ways to measure centrality (Borgatti et al. 2013, pp. 163–80), it follows that there are also different ways in which social prominence may or may not result from structural prominence in the network. Applications of centrality measures in the social sciences may draw on Bourdieu's (1986) concept of capital, which can be variously defined in terms of economic, social, cultural, and symbolic forms. These are important to separate out, however, and often are not made explicit. An early application of centrality measures to study political centralization is Mizaguchi's (2009) study of early state formation in Japan, which showed that settlements with higher centrality scores in one period became politically prominent in later networks. In another example, Mills et al. (2013a,b; 2015) considered the dynamics of networks before, during, and after long-distance migration. Migrant enclaves were found to have low centrality initially but became as central as firstcomers after a generation or two through their manipulation of symbolic capital in the form of polychrome ceramics with ideological connotations.

By contrast, theories of overall network structure focus on whole network attributes. Whole network models applied to archaeological networks include the density of ties or cohesion (Mullins 2016), the presence of subgroups or components (Blake 2014a, Buchanan et al. 2016, Jennings 2016), the extent to which node sizes or other properties conform to "scale-free" or power law distributions such as through preferential attachment (Haas et al. 2015), and how random ties may produce "small worlds" (Coward 2010).

Brughmans (2013b) summarized many of these applications under the header of "complex networks and social physics" to underscore their use in complexity science and physics and commented that "few archaeologists have combined both SNA techniques and complex network modeling" (p. 647). This situation is now changing as more archaeologists are integrating the two through network simulations, especially ABMs, which provide experimentally derived models for comparison with empirical network analyses (e.g., Crabtree 2015, Graham 2006, Graham & Weingart 2015, Kandler & Caccioli 2016, Ossa 2013, Östborn & Gerding 2016, Watts & Ossa 2016).

These overarching theories provide models of how relational worlds work. They have been applied to a wide range of archaeological research questions, including the diffusion of innovations (e.g., Kandler & Caccioli 2016; Mills & Peeples 2018; Östborn & Gerding 2015, 2016), religious and other social movements (Borck & Mills 2017; Collar 2007, 2013a,b; Peeples 2011, 2018), identity (Blake 2013, 2014b; Hart & Englebrecht 2012; Peeples 2011, 2018), migration (Mills et al. 2013a,b, 2015, 2016), and political centralization and the development of hierarchies (Fulminante 2012, Mizoguchi 2009). Each research question requires that the choice of nodes and ties between them be matched to the network question as discussed below.

Archaeologists have begun to refer to network approaches more generally as a paradigm rather than as a theory because it incorporates multiple possible theoretical perspectives (Fulminante 2014, Kristiansen 2014). In their introduction to a recent handbook on SNA, sociologists Marin & Wellman (2011) also describe SNA as a paradigm and not as a method or a theory. As they point out, there is nothing intrinsic to SNA that demands one theoretical approach or another, proposing instead that only relations matter. On the one hand, this theoretical ecumenicalism has fostered a multidisciplinary network of researchers in archaeology in a very short period of time. On the other hand, the rapid pace has also resulted in separate strands of research that could be more effectively bridged, particularly the intersection of network theory with social theory. The overarching network theory linking current archaeological approaches is that connections define probabilities for interaction in the past, the structure of those interactions, and how position in the network creates both opportunities and constraints for actors.

NETWORK REPRESENTATION AND ARCHAEOLOGICAL INTERPRETATION

The basic premise of SNA is that it looks at the relationships among entities or actors (the nodes or vertices) through their connections or ties. Two of the most important considerations in archaeological applications are how to define the boundary of the network (see the sidebar titled Types of Networks and Network Boundaries) and what constitutes a tie.

Archaeology is replete with evidence of ties, including shared spatial, material, biological, and ideological connections. Each one of these requires a clear connection between human behavior—what we are seeking to understand in the past—and archaeological evidence. Otherwise, the use of SNA may end up being a "black box" (Sindbæk 2013) with little relationship between data and

TYPES OF NETWORKS AND NETWORK BOUNDARIES

Network analyses are of two basic kinds: ego networks and whole networks. Ego networks consist of one node and all nodes to which they are tied. Mol and colleagues (2015) constructed ego networks for the Caribbean island of Saba on the basis of the provenance of materials from all other islands. Elizabeth Greene's ongoing analysis of shipwreck contents treats each ship as an "ego" with ties to all the places represented by her cargo. By contrast, whole networks include all nodes in a specific area or defined by a specific criterion, whether or not they are connected, such as all settlements within a region. The term "whole network" is somewhat of a misnomer because the boundaries or samples, as in any other archaeological analysis, are defined by the archaeological problem. This is the "nominal" perspective in SNA, which contrasts with the "realist" or more emic perspective (Laumann et al. 1992). Whole networks are further divided into one-mode networks, two-mode networks, and multimodal networks. One-mode networks are ties between similar kinds of nodes, such as households or settlements. Two-mode networks, or affiliation networks, are ties between nodes of two different kinds. Multimodal networks are an important area of future applications in archaeology.

theory (Isaksen 2013). Collar et al. (2015) used the abstract representation presented by Brandes and his colleagues (2013, figure 1) to discuss the process by which archaeological networks are studied. First, the past phenomenon of interest must be identified, such as an economic relationship between individuals or settlements. Second, an abstraction is made, such as the flow of goods. And third, that abstraction is converted to actual network data, which are the items shown to have been exchanged between each pair of nodes. In all SNA applications in archaeology, the inferential process can be broken down into these three components.

Archaeological networks are constructed using historical, spatial, and/or material culture data. These families of networks define much of the field today. Archaeologists have also contributed to research on food webs (e.g., Crabtree et al. 2017, Dunne et al. 2016), which are important ways of integrating diverse data sources to understand predator–prey relations and how extinctions may affect network stability and resilience. In addition, experimental or simulated networks may be used, independently or in tandem with empirical data sources.

As with any archaeological analyses, when data are sparse, a network approach must be used cautiously. Formal network analyses reveal the structure of the data rather than necessarily the structure of the actual community in the past (Larson 2013, p. 242). Social network analyses that are based on empirical data are no different from any other quantitative analysis in this regard—attention should be paid to issues such as sampling and formation processes. But neither should network approaches be viewed as more susceptible to these issues than other quantitative analyses. Many network analysts employ a range of sensitivity analyses such as exponential random graph models (ERGMs) (e.g., Brughmans et al. 2015), random resampling of assemblages and nodes (e.g., Mills et al. 2013b), and other assessments of the robustness or reliability of networks (Düring 2016, Gjesfjeld & Phillips 2013, Peeples et al. 2016) that warrant wider incorporation.

Historical Networks

Archaeological networks are not usually the face-to-face social networks that are studied in sociology or sociocultural anthropology. Only in a limited number of cases are individual interactions accessible through archaeological data, such as in periods with documentary or epigraphic evidence. While all archaeological networks are historical to some degree and investigation of long-term or dynamic networks is one of the major strengths of archaeology (Terrell 2013), the use of documents and other text-aided sources for constructing ties fits well with a wide area of research on historical networks in other disciplines.

Historical network analysis by archaeologists is still in its infancy. Orser (2005) suggested many ways that historical archaeologists might benefit from a network perspective, although he did not apply formal methods. Mediterranean archaeologists working in historic periods have made the most use of SNA. Graham's (2006) analysis of the Antonine itineraries used several different travelers' routes to show the structure of Roman provincial communication networks, which extended from Britain to Asia Minor. By combining this approach with ABMs, he was also able to show which areas in the Roman Empire were more likely to diffuse information and materials more rapidly than others and how the density of inscriptions by province covaried with these routes. Other compelling SNA applications to Mediterranean archaeology include analyses of the reconstruction of elite interaction based on the Amarna letters (Cline & Cline 2015) and Larson's (2013) work on Greek sculptors, their apprentices, and cities. In the Americas, Classic Maya political and religious networks have been reconstructed from hieroglyphic evidence to investigate bloodletting rituals (Munson et al. 2014) and the diversity of elite ties between Maya centers (Munson & Macri 2009, Scholnick et al. 2013).

Spatial Networks

Formal network approaches to spatial relationships differ from classic settlement pattern models, such as central place theory, because they do not assume that central places are an inevitable historical result of interaction (Fulminante 2012, p. 27; Meijers 2007; Sindbæk 2007, pp. 60–61). Another important point of difference with classical settlement pattern analyses is that most spatial networks are models of potential social interaction and are especially valuable for comparison with other data classes as null models.

Community detection: a method of identifying subgroups in graphs

Spatial connectivities may be based on geographic position using different distance measures (e.g., geodesic, least-cost paths, friction surfaces). Generating data for spatial networks is usually done within a GIS platform. There is a vast literature on the selection of specific spatial distance measures and their methodological advantages and drawbacks (Bevan & Wilson 2013, Conolly & Lake 2006). Different families of spatial models exist for application to archaeological case studies, but only a few have been applied. Knappett and colleagues (Evans 2016, Evans et al. 2009, Knappett et al. 2011, Rivers 2016) review different spatial models and their assumptions, favoring a cost-benefit model to assess the impact of the eruption of Thera on Bronze Age Mediterranean networks. Nonarchaeological reviews of spatial networks (e.g., Barthélemy 2011, Liben-Nowell et al. 2005) are important comparative sources for network models and empirical spatial relations that could be further integrated into archaeological applications.

Spatial networks may be used to simulate social networks (e.g., Graham 2006) and/or as a null model against which other spatial or social network data are then compared (e.g., Plog 1976). Empirical analyses that compare spatial and material networks at different scales show that these networks often deviate from each other. Hart (2012) showed that spatial distance explained little of shared Iroquois pottery design repertoires. He proposed that intrasite dissimilarities could be explained by long-distance movement of subgroups or entire villages or that long-distance interaction was a means for risk reduction. In the pre-Hispanic US Southwest, agriculturalists' spatial networks were variably correlated with the strength of material ties, which also demonstrates the importance of long-distance connections (Hill et al. 2015, Mills et al. 2013b). In this case, many of these long-distance connections were maintained by migrants in different communities after their diaspora into the southern Southwest (Mills et al. 2015).

These results point out how varied the relationship between spatial and social propinquity can be and the importance of maintaining both local and longer-distance connections even within relatively sedentary agricultural communities. We might expect the presence of long-distance ties for forager societies who often maintain these connections to reduce risk, extend marriage networks, and monitor resource availability (Braun & Plog 1982, Fitzhugh et al. 2011, Gjesfjeld 2015, Gjesfjeld & Phillips 2013, Pearce 2014, Phillips 2011, Whallon 2006, Wiessner 1982). Yet, as shown by Coward's (2013, p. 253) comparative analyses of data from a millennium of sites dating to the Epipaleolithic to early Neolithic periods, sedentary settlements and foragers both maintained long-distance relationships. In fact, most groups showed low correlations of social distance—as measured through material culture ties—with spatial distance. Coward cites increasing specialization and the distribution of items with symbolic significance as examples in which geographically long ties were established by relatively sedentary groups.

A subset of spatial networks is based on visibility, often interpreted as communication or visual control networks. Swanson (2003) discusses ethnographic evidence for signaling and applies GIS to hilltop sites in the Casas Grandes region of northern Mexico. He uses the concept of cut points to identify nodes that, when removed, divide the network into subgroups—called community detection—to identify different network components. Swanson found that the visibility or signaling network was robust to failure because cut points were on the edges of the system rather than spatially central. Moreover, an important pilgrimage site had the highest number of connections (i.e., node degree centrality).

Degree centrality: one form of centrality that measures the number of ties for each node

Hub: a network configuration containing nodes with higher-than-average centrality, which may attract new nodes but which also increases vulnerability

Centralization: a global network property measuring the extent to which nodal centrality is concentrated in a single node

Path dependence: the extent to which future action is determined by past actions

Recent studies on visibility networks emphasize whole network properties to assess a range of possible social uses. Brughmans and colleagues (2015) applied visibility analysis to create networks among Iron Age and Roman sites, a high percentage of which are located on hilltops that may have been selected for signaling, visual control, or isolation. Each reason for geographical placement has a different set of network expectations depending on the presence/absence of visibility, visibility directionality, and covisibility of settlements. Like Swanson, they used probability analyses to assess whether locations were intentionally placed for visibility or conformed to a random pattern; by employing ERGMs, they compared the occurrence of particular structural configurations of the network with the frequencies generated by stochastic models (Brughmans et al. 2015, p. 77). During Iberian and Roman periods, the importance of intermediate hubs in the spatial network is brought out, which structured intersettlement interactions. In another visibility analysis more specifically focused on landscapes of conflict, Mullins (2016) compared the network properties of tie density (cohesion) and overall centralization to model and interpret visibility networks in the Moche Valley and Titicaca Basin. He found that there were high values for cohesion (defensive intervisibility among sites in this case), but that network centralization was present only in the Moche Valley, reflecting its higher political centralization.

Transportation corridors such as rivers, roads, and trails are spatial features that lend themselves well to SNA (Apolinaire & Bastourre 2016; Fulminante 2012; Isaksen 2008, 2013; Jenkins 2001; Orengo & Livarda 2016; Pailes 2014; Wernke 2012). Constructed features such as roads literally create path dependence by channeling future movement. Networks based on these features can be tied to a number of processes such as trade, militarism, and religious pilgrimages at the regional scale and interhousehold inequalities at the intrasettlement scale. Spatial network statistics based on corridors of movement can be compared with material culture found at the nodes or with other spatial and formal attributes, such as settlement or household size, providing multiscalar or "multi-net" (van der Leeuw 2013, p. 343) ways of approaching networks.

Intrasite analyses of trail networks compared with public and domestic spaces illustrate how social inequalities may be studied using SNA. Pailes's (2014) analysis of a trail network at the Hohokam site of Cerro Prieto in the US Southwest compared house spatial centrality with floor area, showing that the most central houses were also those with the largest floor areas. Wernke's (2012) intrasite analysis of trails at an early colonial site in highland Peru calculated pathways from each house to the indigenous Inka ceremonial plaza and the Franciscan colonial plaza. Houses were rank ordered according to their access, and the results showed how those structures closest to the original plaza became marginalized and those structures close to the Franciscan-initiated plaza became correspondingly more important—even though the two plazas are close in absolute (Euclidean) space. In both cases, the result was not intuitively obvious without tracing pathways through the sites and converting houses to nodes and interhouse pathways to ties.

Regional fluvial networks can be treated as models for comparison with other attributes such as settlement size or with the flow of materials to examine mercantilism and the emergence of regional power structures. Fulminante's (2012) longitudinal study of central Italian spatial networks from the Final Bronze to Archaic Ages compared settlement centrality indices with settlement size on the basis of point location, roads, and rivers. Fluvial networks were found to be more important earlier on, whereas terrestrial routes later became more prominent. Another regional analysis of a fluvial network, conducted by Apolinaire & Bastourre (2016) for pre-Hispanic Argentinian settlements, found that the largest sites were also those with the highest spatial centrality measures. Both of these studies show how spatial and social prominence are related and how regional scale inequalities may form and endure.

Similarly, Roman roads have been the focus of many experimental and empirical SNA applications as proxies for regional interaction and the diffusion of economic and noneconomic indicators. Combining GIS, SNA, and the distribution of imported plants in Britain, Orengo & Livarda (2016) were able to show which cities were most prominent in Roman commercial networks and identify hypothetical routes of import within the global Roman economy.

Material Networks

SNA based on material culture can be used to address a number of anthropological questions, including shared identities, the structure of power relationships, the diffusion/transmission of technological innovations, and participation in ideological and other social movements. Material culture that can be used to construct networks includes artifacts, architecture, and features from a variety of contexts, including mortuary assemblages. Network connections built on material culture ties employ data on shared raw material provenance, technological styles, design motifs, artifact forms, and inferred symbolic uses, depending on the archaeologists' problem orientation.

SNA applied to different kinds of material culture may be based on presence/absence data or frequencies of objects in assemblages. Ties based on shared assemblage attributes draw on measures such as the Brainerd-Robinson statistic (Brainerd 1951, Robinson 1951), which has been widely employed by archaeologists using SNA (e.g., Freund & Batist 2014; Golitko et al. 2012; Hart & Englebrecht 2012; Mills et al. 2013a,b, 2015; Peeples 2011, 2018; Peeples et al. 2016; Peeples & Roberts 2013; Plog 1976). The various ways to calculate similarity indices is systematically reviewed by Östborn & Gerding (2014), including the use of presence/absence data. Presence/absence data may be especially useful for small sample sizes, such as items found in mortuary assemblages (Sosna et al. 2012) or for especially rare items. Thresholds in similarity scores are applied to produce visualizations, but weighted values are best retained when possible (Peeples & Roberts 2013). The inference made in using material culture is that higher similarity scores indicate greater likelihood of shared social relations, but the specific nature of that relationship depends on the archaeologists' bridging arguments regarding shared procurement, production, distribution, and/or consumption.

Constructing formal networks of interaction from shared procurement of raw materials through chemical and/or mineralogical provenance analyses depends on several underlying assumptions, none of which are unique to SNA: (*a*) precision and accuracy of procurement and/or production area identifications, (*b*) sample size adequacy and issues of unclassified samples, (*c*) comparability of compositional methods, and (*d*) knowledge of whether items passed through other settlements before reaching consumers. SNA based on provenance data may not be possible because the area of production is not pinpointed but rather a larger region defined by chemical compositional reference groups and/or geologically similar regions. Even if point locations can be derived, the ties between settlements cannot always be assumed to be directed, especially if sources are located away from settlements (e.g., obsidian quarry areas), nor can they be assumed to move along a least cost or down-the-line fashion (Sindbæk 2007, p. 61). Tsirogiannis & Tsirogiannis (2016) discuss how objects may move through multiple hands to get to their final consumers and how transaction paths might be detected in a network. Their example, based on historical networks, provides a model for potential archaeological application.

Most provenance-based networks are two-mode networks in that one set of nodes consists of settlements and another set consists of raw material sources. These networks are usually treated as one-mode networks—i.e., ties are drawn between settlements even though the underlying connections are between settlements and sources. In fact, nearly all archaeological material networks are two-mode or affiliation networks, connected by shared production sources, technological practices, or shared consumption. The importance of affiliation networks has been long recognized in sociology (Breiger 1974) and could be more explicitly addressed by archaeologists. Different network statistics and topologies result from treating these as two-mode networks throughout the analysis, rather than collapsing them into a single mode.

Strong tie: ties representing marked or close relationships such as marriage, descent, or close friends, and/or membership in the same subgroup

Although many archaeologists treat provenance-based networks as "exchange networks," the above limitations suggest that this interpretation may be too restrictive. Not all linkages that are based on the movement of materials are necessarily indicative of exchange. The movement of objects may also be through pilgrimages, seasonal use of an area, or human migration. Different modes of acquisition and distribution must also be taken into account as alternatives to exchange. Nonetheless, provenance-based material networks are still considered one of the foremost ways in which interaction can be measured archaeologically, whether or not employing SNA.

Obsidian is a particularly useful material for SNA because of its relative chemical homogeneity within, and heterogeneity between, sources. Network analyses of a large database of Mesoamerican obsidian show the potential of macroregional-scale SNA (Golitko et al. 2012, Golitko & Feinman 2015, Weidele et al. 2016). They demonstrate distinctive groups of interacting settlements within the region, the increasing prominence of coastal routes over time, and the relative importance of Gulf versus Pacific coastal sources and settlements. Western Mediterranean Neolithic-period obsidian networks analyzed by Freund & Batist (2014) identified subgroups within a chronological sequence of networks. Their results show greater heterogeneity in the network over time and a shift from down-the-line to more restricted, maritime distribution associated with more powerful settlements.

Intraregional exchange networks based on ceramic provenance data have been analyzed in many areas. The presence of community-scale ceramic specialization allowed Bernardini (2007) to reconstruct directed networks of exchange and consumption in the greater Hopi region of the Southwest. In a Kuril Islands example, however, intraregional exchange networks based on ceramic compositional data were difficult to assess (Gjesfjeld & Phillips 2013). Three alternative networks of production and distribution—local production, reciprocity, and central place—were modeled, but the resolution of the provenance data was too coarse to accurately reconstruct intraregional exchange or the models were too restrictive or both.

In addition to ties based on compositional similarities, analysts have incorporated technological style as part of communities of practice approaches in network analyses. Technological style attributes represent interactions at a relatively small scale, and especially participation in learning communities, which are usually characterized by strong ties. Peeples (2011, 2018) uses SNA to compare different material networks on the basis of multiple variables, including technological attributes of pottery coiling methods, ceramic compositional analyses, and variation in construction of architectural features. Whereas some networks were more local, others were more spatially extensive. Drawing on the distinction between categorical and relational identities developed by the New York school of historical sociologists and political scientists (Mische 2011), Peeples (2011, 2018) suggests that some materials represent large-scale collective categorical identities, whereas others represent relational identities based on exchange or kinship. In material terms, the former may be expressed through symbolic and active styles, whereas the latter are better approached through technological features indicative of communities of practice and apprenticeship (Lave & Wenger 1991, Wenger 1998).

Some artifact classes may be especially useful in looking at shared identities at both the categorical and relational levels owing to their symbolic content or active style. Clothing and ornaments, for example, are often active ways in which identities are expressed. These may be provenance based, but recent applications have focused largely on consumption rather than on production. Blake (2013; 2014a,b) used ornaments and a variety of other distinctive artifact classes to construct similarity networks throughout Bronze Age Italy. Her analyses showed the emergence of regional identities through shared consumption much earlier than previously thought. She draws on the concept of path dependence to express how local identities became entrenched within different subareas.

Homophily: the tendency for nodes to develop ties with like nodes

Embeddedness: the degree to which a node or subgroup is tied to other nodes or subgroups in the network

Using a database of Iroquois ceramics, which evince visually distinctive decorative designs on jar collars, Hart and colleagues have applied SNA to questions about regional identities, coalescence, and the formation of political confederacies (Hart et al. 2016; Hart & Englebrecht 2012, 2017). They argue that the high visibility of decoration on the collars provided a means of social signaling and that similarities in designs were ways in which relationships were expressed that were not equivalent to ethnic markers. As such, Hart and colleagues (2016) look at social signaling networks as shared participation in ethnically heterogeneous communities that were the result of increasing coalescence (p. 20).

The participation of Native Americans in global-scale networks following colonialism was recently demonstrated by Blair (2016), who used a multimodal SNA approach. Chemical compositional analyses of beads from Indigenous burials at the site of Mission Santa Catalina de Guale show how these individuals were linked to different producers in Europe. By looking at the consumption side of the networks, however, Blair takes these analyses to a new level to show how beads were related to each other, how beads and individuals were related, and how individuals were tied to each other through their shared consumption. He draws on Wenger's (1998, p. 127; see also Roddick 2016) concept of "constellations of practice," which crosscut different communities of practice to produce more global relationships out of local interactions.

Drawing out the ways in which different networks of practice are reproduced through larger-scale networks, Mills (2016) also employed Wenger's concept of constellations of practice to show how multiple networks of practice may operate simultaneously to produce more global structures. One of the ways that these constellations are manifested is through "boundary objects" (Roddick 2016; Wenger 1998, p. 107), which, rather than marking boundaries, form bridges that link communities of practice. Mills argues that decorated ceramics, especially serving bowls, were boundary objects in that they were produced and used by different communities of practice but were consumed in larger constellations of shared consumption.

These larger constellations allowed the Southwest Social Networks Project to investigate how migration transformed social networks across a swath of the US Southwest in the period between AD 1200 and 1500 (Mills et al. 2013a,b, 2015). At the regional scale the depopulated northern network components were dramatically replaced by those located in the Transition Zone and southern valleys of Arizona. Borck et al. (2015) found that depopulated areas were highly homophilous in terms of material culture and disembedded from regional networks, showing how low population density and isolation resulted in social instability and migration. Migrants found niches in already occupied areas, especially the physiographic Transition Zone, which also had low population densities. Peeples & Haas (2013) demonstrated that the settlements in the Transition Zone were in positions of brokerage as measured through weak tie strength (see also Peeples & Mills 2018).

DISCUSSION AND FUTURE DIRECTIONS

As this review shows, a number of theoretical approaches and archaeological settings have been used in SNA. Explicit theoretical approaches include practice (e.g., Blair 2016, Knappett 2011, Mills 2016), Marxist (Iacono 2016), human behavioral ecology (e.g., Gjesfjeld 2015), complexity (Crabtree 2015), and entanglement theories (Hodder & Mol 2016, Mol 2014, Nelson & Kassabaum 2014), among others. SNA has been applied to different social scales from foragers to empires, different spatial scales from single settlements to macroregions, and different temporal spans from single generations to centuries. What links these different theories and archaeological settings is their emphasis on connections or ties to define relationships and, in many cases, their change over time. Those studies that look at network dynamics have been especially useful because they take advantage of archaeology's time depth, adding to the literature on more contemporary network studies by other disciplines.

Some researchers argue that anything that is formally presented using a structural network approach cannot represent the "messiness" or entanglements of reality (Hodder 2012). Critics often cite Latourean actor–network theory and Ingold's (2007) concept of meshworks as examples of the complexity of human (and nonhuman) lives (see discussions in Fulminante 2014, Van Oyen 2016a,b). In a recent review on networks and power, Schortman (2014) contrasts two general approaches that emerge from critiques such as these as between structure- and agency-based approaches.

Such debates about network approaches have been especially prominent in sociological theory for at least two decades but are not framed solely in terms of structure versus agency. For example, a conceptual "cultural hole" (Pachuki & Breiger 2010) has been identified between what the sociologists call network and cultural analyses. Cultural analyses emphasize "meaning practice and discourse that enable social structure and structural holes" (p. 219; see also Erikson 2013). They build on the foundational piece by Emirbayer (1997), which helped establish the field of "relational sociology" and which he contrasts with substantialist perspectives on networks. Relational approaches, as defined by Emirbayer, emphasize the process of social transactions, whereas substantialist approaches view interaction in terms of substances or properties. Social transactions can occur in a variety of domains, as outlined by White [2008 (1992)] in his concept of "network-domains" or "netdoms," which provide alternative contexts for interactions. Similarly, Mische (2011, p. 80) identifies several approaches emerging out of research in sociology on networks and how "these conversations propose a new theoretical agenda that highlights the way in which communicative interaction and the performance of social relations mediate between structure and agency across a wide range of social phenomena." Knox et al. (2006) refer to these works as the third generation of SNA studies in sociology and call for more focused application in anthropology. Importantly, these researchers all may employ formal network methods and theories, rather than rejecting structural approaches outright. The challenge for archaeologists is to bring these concepts to bear using historical, spatial, and/or material evidence. Peeples (2011, 2018) is one of the few to actively engage with this literature in his approach to past identities at different scales.

The SNA literature's current theoretical ecumenicalism suggests that many archaeologists will continue to pursue quite different research agendas ranging from those more aligned with network science to those more engaged with practice, materiality, and agency. Although there are advantages to the big tent approach, especially while network applications are enjoying a sharp uptake (Collar et al. 2015), there is considerable room for more focused attention on how to integrate different perspectives within archaeology. This will help bridge the current structural hole in SNA approaches noted above.

Work on bridging archaeological approaches to networks has begun, especially through connectivities based on the use of archaeological materials with high symbolic or ideological content, analyses that incorporate nonhumans (things, animals) as actors or nodes in the network, recognition of the important symbolic and relational role of boundary objects, and interpretations that emphasize how network position and overall network structure or topology simultaneously create opportunities and constraints for individual actors. Further work on spanning disciplinary differences in relational theories of networks is needed to build on these new directions.

An important future issue is in how to incorporate multiple networks into analyses. Networks can be multiscalar in spatial, temporal, social, and material terms. Multiscalar networks may also refer to the use of different classes of materials, such as pottery provenance and decoration, to look at connections. Multiplex networks are possible by layering different network structures on top of each other (see Coward 2013, p. 249; Knappett 2014). Indeed, this is one of the great contributions of historical networks research (e.g., Padgett & Powell 2012) and at the forefront of SNA in other fields.

It is clear that GIS will continue to play an important part in network analyses, not just for analyzing networks based on spatial ties such as visibility, but also as a means to compare network results on the basis of nonspatial ties. Networks based on spatial distance measures offer a null model for considering how network structures differ from expected characteristics. The regular incorporation of GIS and SNA approaches will require, however, expertise in a range of analytical methods and theories and/or collaborations among researchers.

Another future direction is to tie together natural and human systems to investigate the social network effects of disasters. These may be events, such as volcanic eruptions (Riede 2014), or longer changes such as decadal or multidecadal droughts (Borck et al. 2015). They may be the result of naturally or anthropogenically caused processes. Understanding these effects has important implications for public policy and outreach.

Last, future work in SNA in archaeology will benefit from wider interaction with researchers in other disciplines, including sociologists, computer scientists, and political geographers for both methodological and theoretical insights and collaborations. Digital humanities and archaeological synthesis projects, bringing together disparate data sets, will also result in interdisciplinary or multidisciplinary teams joined together in compilations and analyses from multiple perspectives. Native American ontologies have not been explored and would provide alternative ways of defining categories of data to analyze as well as new interpretations.

Whichever theoretical approach taken, network analyses provide models or representations of the interactions among actors and their groups. As models, they can be used in an exploratory fashion and as a way of visualizing or summarizing both small and large data sets. They can also be used to test hypotheses in a traditional confirmatory data analysis approach. The power of network approaches is in how they help archaeologists to think explicitly about relationships, how to measure them, and how they are expressed at different material, social, spatial, and temporal scales. With network metaphors so abundant today, SNA approaches have much potential for archaeological narratives about the past that resonate with the public in addition to their ability to enhance interdisciplinary collaborations and to form new interpretations of the past.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

I am grateful to the members of the Southwest Social Networks Project who have provided insights into many of the topics discussed here. I especially thank Ronald Breiger, Matthew Peeples, and John Roberts for their helpful comments on this article.

LITERATURE CITED

Anthony DW. 1990. Migration in archaeology: the baby and the bathwater? *Am. Anthropol.* 92(4):895–914

Apolinaire E, Bastourre L. 2016. Nets and canoes: a network approach to the pre-Hispanic settlement system in the Upper Delta of the Paraná River (Argentina). *J. Anthropol. Archaeol.* 44:56–68

Barnes JA. 1954. Class and committees in a Norwegian Island Parish. *Hum. Relat.* 7:39–58

Barthélemy M. 2011. Spatial networks. *Phys. Rep.* 499(1–3):1–101

Bernardini W. 2007. Jeddito Yellow Ware and Hopi social networks. *Kiva* 72(3):295–328

Bevan A, Wilson A. 2013. Models of settlement hierarchy based on partial evidence. *J. Archaeol. Sci.* 40:2415–27

Blair EH. 2016. Glass beads and constellations of practice. In *Knowledge in Motion: Constellations of Learning Across Time and Space*, ed. AP Roddick, AB Stahl, pp. 97–125. Tucson: Univ. Ariz. Press

Blake E. 2013. Social networks, path dependence, and the rise of ethnic groups in pre-Roman Italy. See Knappett 2013, pp. 203–22

Blake E. 2014a. Dyads and triads in community detection: a view from the Italian Bronze Age. *Nouv. Archéol.* 135:28–31

Blake E. 2014b. *Social Networks and Regional Identity in Bronze Age Italy*. Cambridge, UK: Cambridge Univ. Press

Borck L, Mills BJ. 2017. Approaching an archaeology of choice: consumption, resistance, and religion in the Prehispanic Southwest. In *Foreign Objects: Rethinking Indigenous Consumption in American Archaeology*, ed. CN Cipolla, pp. 29–43. Tucson: Univ. Ariz. Press

Borck L, Mills BJ, Peeples MA, Clark JJ. 2015. Are social networks survival networks? An example from the Late Pre-Hispanic US Southwest. *J. Archaeol. Method Theory* 22(1):33–57

Borgatti SP, Everett MG, Johnson JC. 2013. *Analyzing Social Networks*. Los Angeles: Sage

Provides an introduction to SNA and is useful as an introductory textbook.

Borgatti SP, Halgin DL. 2011. On network theory. *Organ. Sci.* 22:1168–81

Bourdieu P. 1986. The forms of capital. In *Handbook of Theory and Research for the Sociology of Education*, ed. J Richardson, pp. 241–58. New York: Greenwood

Brainerd G. 1951. The place of chronological ordering in archaeological analysis. *Am. Antiq.* 16(4):301–13

Brandes U, Robins G, McCranie A, Wasserman S. 2013. What is network science? *Netw. Sci.* 1(1):1–15

Braun DP, Plog S. 1982. Evolution of "tribal" social networks: theory and prehistoric North American evidence. *Am. Antiq.* 47:504–25

Breiger RL. 1974. The duality of persons and groups. *Soc. Forces* 53(2):181–90

Broodbank C. 1993. Ulysses without sails: trade, distance, knowledge and power in the early Cyclades. *World Archaeol.* 24(3):315–31

Brughmans T. 2010. Connecting the dots: towards archaeological network analysis. *Oxf. J. Archaeol.* 29(3):277–303

Brughmans T. 2012. Facebooking the past: a critical social network analysis approach for archaeology. In *Thinking Beyond the Tool: Archaeological Computing and the Interpretative Process*, ed. A Chrysanthi, PM Flores, C Papadopoulos, pp. 191–203. Oxford, UK: Archaeopress

Brughmans T. 2013a. Networks of networks: a citation network analysis of the adoption, use and adaptation of formal network techniques in archaeology. *Lit. Linguist. Comput.* 28(4):538–62

Brughmans T. 2013b. Thinking through networks: a review of formal network methods in archaeology. *J. Archaeol. Method Theory* 20:623–62

Serves as the first extended critical review of SNA in archaeology.

Brughmans T. 2014. The roots and shoots of archaeological network analysis: a citation analysis and review of archaeological use of formal network methods. See Evans & Felder 2014, pp. 18–41

Brughmans T, Collar A, Coward F, eds. 2016. *The Connected Past: Challenges to Network Studies in Archaeology and History*. Oxford, UK: Oxford Univ. Press

Emphasizes methodological and theoretical challenges to SNA in archaeology.

Brughmans T, Keay S, Earl GP. 2015. Understanding inter-settlement visibility in Iron Age and Roman Southern Spain with exponential random graph models for visibility networks. *J. Archaeol. Method Theory* 22(1):58–143

Brughmans T, Peeples MA. 2017. Trends in archaeological networks research: a bibliometric analysis. *J. Hist. Netw. Res.* 1:3–17

Buchanan B, Hamilton MJ, Kilby JD, Gingerich JAM. 2016. Lithic networks reveal early regionalization in late Pleistocene North America. *J. Archaeol. Sci.* 65:114–21

Cegielski WH, Rogers JD. 2016. Rethinking the role of agent-based modeling in archaeology. *J. Anthropol. Archaeol.* 41:283–98

Chorley RJ, Haggett P, eds. 1967. *Models in Geography*. London: Methuen

Cline DH, Cline EH. 2015. Text messages, tablets, and social networks: the "small world" of the Amarna Letters. In *There and Back Again—The Crossroads II*, ed. J Mynářová, P Onderka, P Pavúk, pp. 17–44. Prague: Charles Univ.

Collar A. 2007. Network theory and religious innovation. *Mediterr. Hist. Rev.* 22(1):149–62

Collar A. 2013a. Re-thinking Jewish ethnicity through social network analysis. See Knappett 2013, pp. 223–46

Collar A. 2013b. *Religious Networks in the Roman Empire: The Spread of New Ideas*. Cambridge, UK: Cambridge Univ. Press

Collar A, Coward F, Brughmans T, Mills BJ. 2015. Networks in archaeology: phenomena, abstraction, representation. *J. Archaeol. Method Theory* 22(1):1–32

Conolly J, Lake M. 2006. *Geographical Information Systems in Archaeology*. Cambr. Man. Archaeol. Cambridge, UK: Cambridge Univ. Press

Coward F. 2010. Small worlds, material culture and ancient Near Eastern social networks. *Proc. Br. Acad.* 158:449–79

Coward F. 2013. Grounding the net: social networks, material culture, and geography in the Epipalaeolithic and early Neolithic of the Near East (~21–6,000 cal BCE). See Knappett 2013, pp. 247–80

Crabtree SA. 2015. Inferring Ancestral Pueblo social networks from simulation in the Central Mesa Verde. *J. Archaeol. Method Theory* 22(1):144–81

Crabtree SA, Vaughn LJS, Crabtree NT. 2017. Reconstructing Ancestral Pueblo food webs in the southwestern United States. *J. Archaeol. Sci.* 81:116–27

Davis JL. 1982. Thoughts on prehistoric and archaic Delos. *Temple Univ. Aegean Symp.* 7:23–33

Dunne JA, Maschner H, Betts MW, Huntly N, Russell R, et al. 2016. The roles and impacts of human hunter-gatherers in North Pacific marine food webs. *Sci. Rep.* 6:21179

Düring M. 2016. How reliable are centrality measures for data collected from fragmentary and heterogeneous historical sources? A case study. See Brughmans et al. 2016, pp. 85–102

Emirbayer M. 1997. Manifesto for a relational sociology. *Am. J. Sociol.* 103(2):281–317

Erikson E. 2013. Formalist and relationalist theory in social network analysis. *Sociol. Theory* 31(3):219–42

Evans S, Felder K, eds. 2014. Special Issue: Social Network Perspectives in Archaeology. *Archaeol. Rev. Camb.* 29(1)

Evans T. 2016. Which network model should I use? Towards a quantitative comparison of spatial network models in archaeology. See Brughmans et al. 2016, pp. 149–74

Evans T, Knappett C, Rivers R. 2009. Using statistical physics to understand relational space: a case study from Mediterranean prehistory. In *Complexity Perspectives in Innovation and Social Change*, ed. D Lane, D Pumain, S Van der Leeuw, G West, pp. 451–79. Dordrecht, Neth.: Springer

Fitzhugh B, Phillips SC, Gjesfjeld E. 2011. Modeling hunter-gatherer information networks: an archaeological case study from the Kuril Islands. In *Information and Its Role in Hunter-Gatherer Bands*, ed. R Whallon, W Lovis, R Hitchcock, pp. 85–115. Los Angeles: Cotsen Inst. Archaeol. Press

Freeman LC. 2004. *The Development of Social Network Analysis: A Study in the Sociology of Science*. Vancouver: Empir. Press

Freund KP, Batist Z. 2014. Sardinian obsidian circulation and early maritime navigation in the Neolithic as shown through social network analysis. *J. Island Coast. Archaeol.* 9(3):364–80

Fulminante F. 2012. Social network analysis and the emergence of central places: a case study from Central Italy (*Latium Vetus*). *BABESCH* 87:27–53

Fulminante F. 2014. The network approach: tool or paradigm? See Evans & Felder 2014, pp. 167–78

Gjesfjeld E. 2015. Network analysis of archaeological data from hunter-gatherers: methodological problems and potential solutions. *J. Archaeol. Method Theory* 22(1):182–205

Gjesfjeld EC, Phillips SC. 2013. Evaluating adaptive network strategies with geochemical sourcing data: a case study from the Kuril Islands. See Knappett 2013, pp. 281–306

Golitko M, Feinman GM. 2015. Procurement and distribution of Pre-Hispanic Mesoamerican obsidian 900 BC-AD 1520: a social network analysis. *J. Archaeol. Method Theory* 22(1):206–47

Golitko M, Meierhoff J, Feinman GM, Williams PR. 2012. Complexities of collapse: the evidence of Maya obsidian as revealed by social network graphical analysis. *Antiquity* 86:507–23

Graham S. 2006. Networks, agent-based models and the Antonine itineraries: implications for Roman archaeology. *J. Mediterr. Archaeol.* 19(1):45–64

Presents an introduction to a special issue on SNA in archaeology, including an extensive glossary.

Graham S, Weingart SJ. 2015. The equifinality of archaeological networks: an agent-based exploratory lab approach. *J. Archaeol. Method Theory* 22:248–74

Granovetter M. 1983. The strength of weak ties: a network theory revisited. *Sociol. Theory* 1(1):201–33

Haas WR Jr., Klink CJ, Maggard GJ, Aldenderfer AS. 2015. Settlement-size scaling among prehistoric hunter-gatherer settlement systems in the New World. *PLOS ONE* 10(11):e0140127

Hage P, Harary F. 1996. *Island Networks. Communication, Kinship, and Classification Structures in Oceania*. Cambridge, UK: Cambridge Univ. Press

Harary F. 1969. *Graph Theory*. Reading, MA: Addison-Wesley

Hart JP. 2012. The effects of geographical distances on pottery assemblage similarities: a case study from Northern Iroquoia. *J. Archaeol. Sci.* 39:128–34

Hart JP, Englebrecht W. 2012. Northern Iroquoian ethnic evolution: a social network analysis. *J. Archaeol. Method Theory* 19:322–49

Hart JP, Englebrecht W. 2017. Revisiting Onondaga Iroquois prehistory through social network analysis. In *Process and Meaning in Spatial Archaeology: Investigations into pre-Columbian Iroquoian Space and Time*, ed. EE Jones, JL Creese, pp. 189–214. Boulder: Univ. Press Colo.

Hart JP, Shafie T, Birch J, Dermarkar S, Williamson RF. 2016. Nation building and social signaling in Southern Ontario: A.D. 1350–1650. *PLOS ONE* 11(5):e0156178

Hill JB, Peeples MA, Huntley DL, Carmack HJ. 2015. Spatializing social networks in the late precontact US Southwest. *Adv. Archaeol. Pract.* 3(1):63–77

Hodder I. 2012. *Entangled: An Archaeology of the Relationships between Humans and Things*. Chichester, UK: Wiley

Hodder I, Mol A. 2016. Network analysis and entanglement. *J. Archaeol. Method Theory* 23(1):1066–94

Hunt T. 1988. Graph theoretic network models for Lapita exchange: a trial application. In *Archaeology of the Lapita Cultural Complex: A Critical Review*, ed. PV Kirch, TL Hunt, pp. 135–55. Res. Rep. 5. Seattle: Thomas Burke Meml. Wash. State Mus.

Hutson S. 2010. *Dwelling, Identity, and the Maya: Relational Archaeology at Chunchucmil*. Lanham, MD: AltaMira Press

Iacono F. 2016. From networks to society: pottery style and hegemony in Bronze Age Southern Italy. *Camb. Archaeol. J.* 26(1):121–40

Ingold T. 2007. *Lines: A Brief History*. London: Routledge

Irwin-Williams C. 1977. A network model for the analysis of prehistoric trade. In *Exchange Systems in Prehistory*, ed. TK Earle, J Ericson, pp. 141–51. New York: Academic

Isaksen L. 2008. The application of network analysis to ancient transport geography: a case study of Roman Baetica. *Digit. Mediev.* 4: **http://doi.org/10.16995/dm.20**

Isaksen L. 2013. "O what a tangled web we weave"—towards a practice that does not deceive. See Knappett 2013, pp. 43–70

Jenkins D. 2001. A network analysis of Inka roads, administrative centers, and storage facilities. *Ethnohistory* 48(4):655–87

Jennings B. 2016. Exploring Late Bronze Age systems of bronzework production in Switzerland through network science. *Sci. Technol. Archaeol. Res.* 2(1):90–112

Kandler A, Caccioli F. 2016. Networks, homophily, and the spread of innovations. See Brughmans et al. 2016, pp. 175–97

Knappett C. 2011. *An Archaeology of Interaction: Network Perspectives on Material Culture and Society*. Oxford, UK: Oxford Univ. Press

Presents pivotal work on regional interaction and how SNA fits with new relational archaeology

Knappett C, ed. 2013. *Network Analysis in Archaeology: New Approaches to Regional Interaction*. Oxford, UK: Oxford Univ. Press

Collection of papers illustrating the breadth of SNA applications in archaeology

Knappett C. 2014. What *are* social network perspectives in archaeology? See Evans & Felder 2014, pp. 179–84

Knappett C, Evans T, Rivers R. 2011. The Theran eruption and Minoan palatial collapse: new interpretations gained from modelling the maritime network. *Antiquity* 85(329):1008–23

Kristiansen K. 2014. Towards a new paradigm? The third science revolution and its possible consequences in archaeology. *Curr. Swed. Archaeol.* 22:11–34

Larson KA. 2013. A network approach to Hellenistic sculptural production. *J. Mediterr. Archaeol.* 26:235–60

Laumann EO, Marsden PV, Prensky D. 1992. The boundary specification problem in network analysis. In *Research Methods in Social Network Analysis*, ed. LC Freeman, DR White, AK Romney, pp. 61–87. Piscataway, NJ: Trans. Publ.

Lave J, Wenger E. 1991. *Situated Learning: Legitimate Peripheral Participation*. Cambridge, UK: Cambridge Univ. Press

Liben-Nowell D, Novak J, Kumar R, Raghavan P, Tomkins A. 2005. Geographic routing social networks. *PNAS* 102(33):11623–28

Lock G, Pouncett J. 2007. Network analysis in archaeology session introduction: an introduction to network analysis. In *Digital Discovery. Exploring New Frontiers in Human Heritage. Proc. CAA 2006: Comput. Appl. Quant. Methods Archaeol.*, ed. JT Clark, E Hagemeister, pp. 61–63. Budapest: Archaeolingua

Malkin I. 2011. *A Small Greek World: Networks in the Ancient Mediterranean*. Oxford, UK: Oxford Univ. Press

Marin A, Wellman B. 2011. Social network analysis: an introduction. See Scott & Carrington 2011, pp. 11–25

Meijers E. 2007. From central place to network model. Theory and evidence of a paradigm change. *Tijdschr. Voor Econ. En Soc. Geogr.* 98:245–59

Mills BJ. 2016. Communities of consumption: cuisines as constellated networks of situated practice. In *Knowledge in Motion, Constellations of Learning Across Time and Place*, ed. AP Roddick, AB Stahl, pp. 248–70. Tucson: Univ. Ariz. Press

Mills BJ, Clark JJ, Peeples MA. 2016. Migration, skill, and the transformation of social networks in the pre-Hispanic Southwest. *Econ. Anthropol.* 3(2):203–15

Mills BJ, Clark JJ, Peeples MA, Haas WR Jr., Roberts JM Jr., et al. 2013b. Transformation of social networks in the late pre-Hispanic US Southwest. *PNAS* 110(15):5785–90

Mills BJ, Peeples MA. 2018. Reframing diffusion through social network theory. In *Interaction and Connectivity in the Greater Southwest*, ed. KG Harry, B Roth. Boulder: Univ. Press Colo. In press

Mills BJ, Peeples MA, Haas WR Jr., Borck L, Clark JJ, Roberts JM Jr. 2015. Multiscalar perspectives on social networks in the late Prehispanic Southwest. *Am. Antiq.* 80(1):3–24

Mills BJ, Roberts JM Jr., Clark JJ, Haas WR Jr., Huntley D, et al. 2013a. The dynamics of social networks in the Late Prehispanic US Southwest. See Knappett 2013, pp. 181–202

Mische A. 2011. Relational sociology, culture, and agency. See Scott & Carrington 2011, pp. 80–97

Mitchell M. 2006. Complex systems: network thinking. *Artif. Intell.* 170:1194–212

Mizoguchi K. 2009. Nodes and edges: a network approach to hierarchisation and state formation in Japan. *J. Anthropol. Archaeol.* 28(1):14–26

Mol A. 2014. Play-things and the origins of online networks: virtual material culture in multiplayer games. See Evans & Felder 2014, pp. 144–66

Mol AAA, Hoogland MLP, Hofman CL. 2015. Remotely local: ego-networks of late pre-colonial (AD 1000–1450) Saba, Northeastern Caribbean. *J. Archaeol. Method Theory* 22(1):275–305

Mullins P. 2016. Webs of defense: structure and meaning of defensive visibility networks in Prehispanic Peru. *J. Archaeol. Sci. Rep.* 8:346–55

Munson J, Amati V, Collard M, Macri MJ. 2014. Classic Maya bloodletting and the cultural evolution of religious rituals: quantifying patterns of variation in hieroglyphic texts. *PLOS ONE* 9(9):e107982

Munson JL, Macri MJ. 2009. Sociopolitical network interactions: a case study of the Classic Maya. *J. Anthropol. Archaeol.* 28(4):424–38

Nelson ES, Kassabaum MC. 2014. Expanding social networks through ritual deposition: a case study from the Lower Mississippi Valley. See Evans & Felder 2014, pp. 103–28

Newman MEJ. 2010. *Networks: An Introduction*. New York: Oxford Univ. Press

Provides a major interdisciplinary overview of networks, useful as an advanced textbook.

Orengo HA, Livarda A. 2016. The seeds of commerce: a network analysis-based approach to the Romano-British transport system. *J. Archaeol. Sci.* 66:21–35

Orser CE Jr. 2005. Network theory and the archaeology of modern history. In *Global Archaeological Theory: Contextual Voices and Contemporary Thoughts*, ed. PP Funari, A Zarankin, E Stovel, pp. 77–95. New York: Kluwer Acad.

Ossa A. 2013. Using network expectations to identify multiple exchange systems: a case study from Postclassic Sauce and its hinterland in Veracruz, Mexico. *J. Anthropol. Archaeol.* 32:415–32

Östborn P, Gerding H. 2014. Network analysis of archaeological data: a systematic approach. *J. Archaeol. Sci.* 46:75–88

Provides a comprehensive overview of formal measures for constructing ties for SNA.

Östborn P, Gerding H. 2015. The diffusion of fired bricks in Hellenistic Europe: a similarity network analysis. *J. Archaeol. Method Theory* 22(1):306–44

Östborn P, Gerding H. 2016. Brick makers, builders and commissioners as agents in the diffusion of Hellenistic fired bricks: choosing social models to fit archaeological data. *J. Greek Archaeol.* 1:233–70

Pachuki MA, Breiger RL. 2010. Cultural holes: beyond relationality in social networks and culture. *Annu. Rev. Sociol.* 36:205–24

Padgett JF, Powell WW. 2012. *The Emergence of Organizations and Markets*. Princeton, NJ: Princeton Univ. Press

Pailes M. 2014. Social network analysis of Early Classic Hohokam corporate group inequality. *Am. Antiq.* 79(3):465–86

Pearce E. 2014. Modelling mechanisms of social network maintenance in hunter-gatherers. *J. Archaeol. Sci.* 50:403–13

Peeples MA. 2011. *Identity and social transformation in the Prehispanic Cibola World: AD 1150–1325*. PhD Diss. Tempe: Ariz. State Univ.

Peeples MA. 2018. *Connected Communities: Social Networks, Identity, and Social Change in the Ancient Cibola World*. Tucson: Univ. Ariz. Press. In press

Peeples MA, Haas WR Jr. 2013. Brokerage and social capital in the Prehispanic U.S. Southwest. *Am. Anthropol.* 115(2):232–47

Peeples MA, Mills BJ. 2018. Frontiers of marginality and mediation in the U.S. Southwest: a social networks perspective. In *Social Identity in Frontier and Borderland Communities of the North American Southwest*, ed. KG Harry, S Herr. Boulder: Univ. Press Colo. In press

Peeples MA, Mills BJ, Haas WR Jr., Clark JJ, Roberts JM Jr. 2016. Analytical challenges for the application of network analyses in archaeology. See Brughmans et al. 2016, pp. 59–84

Peeples MA, Roberts JM Jr. 2013. To binarize or not to binarize: relational data and the construction of archaeological networks. *J. Archaeol. Sci.* 40(7):3001–10

Peregrine P. 1991. A graph-theoretic approach to the evolution of Cahokia. *Am. Antiq.* 56(1):66–75

Phillips SC. 2011. *Networked glass: lithic raw material consumption and social networks in the Kuril Islands, Far Eastern Russia*. PhD Diss. Univ. Wash., Seattle

Plog S. 1976. Measurement of prehistoric interaction between communities. In *The Early Mesoamerican Village*, ed. KV Flannery, pp. 255–72. New York: Academic

Riede F. 2014. Eruptions and ruptures—a social network perspective on vulnerability and impact of the Laacher See Eruption (C. 13,000 BP) on Late Glacial hunter-gatherers in northern Europe. See Evans & Felder 2014, pp. 67–102

Rivers R. 2016. Can archaeological models always fulfill our prejudices. See Brughmans et al. 2016, pp. 123–47

Robinson WS. 1951. A method for chronologically ordering archaeological deposits. *Am. Antiq.* 16(4):293–301

Roddick AP. 2016. Scalar relations: a juxtaposition of craft learning in the Lake Titicaca Basin. In *Knowledge in Motion: Constellations of Learning Across Time and Place*, ed. AP Roddick, AB Stahl, pp. 126–54. Tucson: Univ. Ariz. Press

Rothman MS. 1987. Graph theory and the interpretation of regional survey data. *Paléorient* 13(2):73–91

Scholnick JB, Munson JL, Macri MJ. 2013. Positioning power in a multi-relational framework: a social network analysis of Classic Maya political rhetoric. See Knappett 2013, pp. 95–124

Schortman EM. 2014. Networks of power in archaeology. *Annu. Rev. Anthropol.* 43:167–82

Scott J, Carrington P, eds. 2011. *The SAGE Handbook of Social Network Analysis*. London: Sage

Sindbæk SM. 2007. The small world of the Vikings: networks in Early Medieval communication and exchange. *Nor. Archaeol. Rev.* 40:59–74

Sindbæk SM. 2013. Broken links and black boxes: material affiliations and contextual network synthesis in the Viking World. See Knappett 2013, pp. 71–94

Sosna D, Galeta P, Šmejda L, Sladek V, Bruzek J. 2012. Burials and graphs: relational approach to mortuary analysis. *Soc. Sci. Comput. Rev.* 31(1):56–70

Stovel K, Shaw L. 2012. Brokerage. *Annu. Rev. Sociol.* 38:139–58

Swanson S. 2003. Documenting prehistoric communication networks: a case study in the Paquimé polity. *Am. Antiq.* 68(4):753–67

Terrell JE. 1977. Human biogeography in the Solomon Islands. *Fieldiana Anthropol.* 68(1):1–47
Terrell JE. 2013. Social network analysis and the practice of history. See Knappett 2013, pp. 17–42
Tsirogiannis C, Tsirogiannis C. 2016. Uncovering the hidden routes: algorithms for identifying paths and missing links in trade networks. See Brughmans et al. 2016, pp. 103–22
Van der Leeuw SE. 2013. Archaeology, networks, information processing, and beyond. See Knappett 2013, pp. 335–48
Van Oyen A. 2016a. Historicising material agency: from relations to relational constellations. *J. Archaeol. Method Theory* 23(1):354–78
Van Oyen A. 2016b. Networks or work-nets? Actor-network theory and multiple social topologies in the production of Roman *Terra Sigillata*. See Brughmans et al. 2016, pp. 35–56
Wasserman SJ, Faust K. 1994. *Social Network Analysis: Methods and Applications.* Cambridge, UK: Cambridge Univ. Press
Watts C, ed. 2013. *Relational Archaeologies: Humans, Animals, Things*. New York: Routledge
Watts DJ, Strogatz SH. 1998. Collective dynamics of "small-world" networks. *Nature* 393:440–42
Watts J, Ossa A. 2016. Exchange network topologies and agent-based modeling: economies of the Sedentary-Period Hohokam. *Am. Antiq.* 81(4):623–44
Weidele D, van Garderen D, Golitko M, Feinman GM, Brandes U. 2016. On graphical representations of similarity in geo-temporal frequency data. *J. Archaeol. Sci.* 72:105–16
Wenger E. 1998. *Communities of Practice: Learning, Meaning, and Identity*. Cambridge, UK: Cambridge Univ. Press
Wernke SA. 2012. Spatial network analysis of a terminal Prehispanic and early colonial settlement in highland Peru. *J. Archaeol. Sci.* 39(4):1111–22
Whallon R. 2006. Social networks and information: non-"utilitarian" mobility among hunter-gatherers. *J. Anthropol. Archaeol.* 25:259–70
White HC. 2008 (1992). *Identity and Control: How Social Formations Emerge*. Princeton, NJ: Princeton Univ. Press. 2nd ed.
Wiessner P. 1982. Risk, reciprocity and social influences on !Kung San economics. In *Politics and History in Band Societies*, ed. E Leacock, R Lee, pp. 61–84. Cambridge, UK: Cambridge Univ. Press

Provides one of the best overviews of SNA in sociology.

RELATED RESOURCES

Bastian M, Heymann S, Jacomy M. 2009. *Gephi: an open source software for exploring and manipulating networks.* Int. AAAI Conf. Weblogs Soc. Media. **https://gephi.org/publications/gephi-bastian-feb09.pdf**
Borgatti SP, Everett MG, Freeman LC. 2002. *UCINET for Windows: software for social network analysis.* Cambridge, MA: Anal. Technol.
Carrington PJ, Scott J, Wasserman S, eds. 2005. *Models and Methods in Social Network Analysis.* New York: Cambridge Univ. Press
De Nooy W, Mrvar A, Batagelj V. 2011. *Exploratory Social Network Analysis with Pajek.* Cambridge, UK: Cambridge Univ. Press. 2nd ed.
Hennig M, Brandes U, Pfeffer J, Mergel I. 2012. *Studying Social Networks: A Guide to Empirical Research.* New York: Campus Verlag
Scott J. 2013. *Social Network Analysis: A Handbook.* Los Angeles: Sage. 3rd ed.
Wilensky U, Rand W. 2015. *An Introduction to Agent-Based Modeling: Modeling Natural, Social and Engineered Complex Systems with Netlogo.* Cambridge, MA: MIT Press